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TECHNICAL REPORT

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AN EVALUATION OF THE EFFECTS OF ALTITUDE ON THE HEIGHT VELOCITY DIAGRAM OF A SINGLE ENGINE HELICOPTEI

by William J. Hanley and Gilbert DeVore

Systems Research and Development Service
National Aviation Facilities Experimental Center
Atlantic City, New Jersey

FEDERAL AVIATION AGENCY

Washington, D.C. February 1964

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TECHNICAL REPORT
ADS-1

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WILLIAM J. HANLEY
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SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

February, 1964

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FEDERAL AVIATION AGENCY

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EVALUATION OF THE EFFECTS OF ALTITUDE ON THE HEIGHT-VELOCITY DIAGRAM OF A SINGLE ENGINE HELICOPTER

By William J. Hanley and Gilbert DeVore

SUMMARY

A series of flight tests were conducted at four selected altitudes (sea level, 4000 feet, 7000 feet, and 10,000 feet) to determine the effects of altitude on the height-velocity (H-V) diagram of a light weight, single-rotor, single-engine helicopter. Three gross weights of the helicopter were used. Quantitative and qualitative test data were collected to determine how the height-velocity diagram varies with density altitude. The data were analyzed to determine a means of calculating the height-velocity diagrams for various density altitudes from flight test data recorded at one density altitude.

Results disclosed a family of curves showing that increases in either density altitude or gross weight increased either the airspeed or the height above the ground required for a safe autorotation landing.

Analysis of the results led to the derivation of three linear equations which expressed the relationship of critical points of the height-velocity diagram of the test helicopter for various gross weights and density altitudes. Flight test H-V diagram data recorded at one density altitude for two or more gross weights of the helicopter can be used to determine the constants of the linear equations. The three linear equations may then be used to calculate the height-velocity diagrams for various other density altitudes and helicopter gross weight.

GLOSSARY OF TERMS AND SYMBOLS

V_{cr}	=	critical velocity mph, CAS. The speed above which an autorotative landing can be made from any height after power failure in the low speed regime.
h_{cr}	=	the height above the ground in feet at which V_{cr} is maximum.
h_{min}	=	the high hover height - the height in feet above the ground from above which a safe autorotative landing can be made after power failure at zero airspeed.
h_{max}	=	the low hover height - the height above the ground in feet from below which a safe autorotative landing can be made after power failure at zero airspeed.
H	=	density altitude at the point of landing.
h	=	height of the helicopter in feet above the ground.
W	=	helicopter weight in pounds.
A	=	rotor disc area in square feet.
CAS	=	calibrated airspeed - indicated airspeed corrected for instrument and position error.

INTRODUCTION

Purpose

Project No. 343-010-01V was undertaken to determine by flight test the effects of altitude on the regimes of flight following power failures, and how these altitude effects are reflected in the magnitude and shape of the height-velocity diagram. A secondary objective was to obtain additional data on the basic helicopter flight parameters to permit correlation with and/or verification of a theoretical approach to the calculation of the effects of altitude on the height-velocity diagram.

Background

Characteristic of the helicopter is its ability to make a safe autorotative landing after an inflight power failure; this characteristic, however, is effective only within definite limits. The capability of a particular helicopter to make a safe autorotative landing is limited by its structural design. Safety of flight presupposes that power failure will occur at combinations of height and forward speed from which recovery can be made during an autorotative descent. The safe operating regimes of flight can be derived experimentally and expressed graphically as a height-velocity (H-V) diagram. Prior to the tests reported under this project, H-V diagrams for a particular helicopter had been constructed from data collected at a single test site where the full effects of altitude could not be explored.

The height-velocity diagram is by definition a chart which defines an envelope of flight[1] with respect to height above the ground and airspeed which should be avoided, for in the event a power failure should occur within this envelope, a safe autorotational landing could not be effected. A typical height-velocity diagram is shown in Figure 1.

A secondary consideration for a safe landing is that of terrain. While the terrain features that might normally be encountered in the execution of an emergency autorotation are many and varied, for test purposes it is customarily assumed that power failure occurs over an airport or firm level ground.

[1] Sometimes referred to in official FAA Rotorcraft Flight Manuals as the Height-Velocity Envelope.

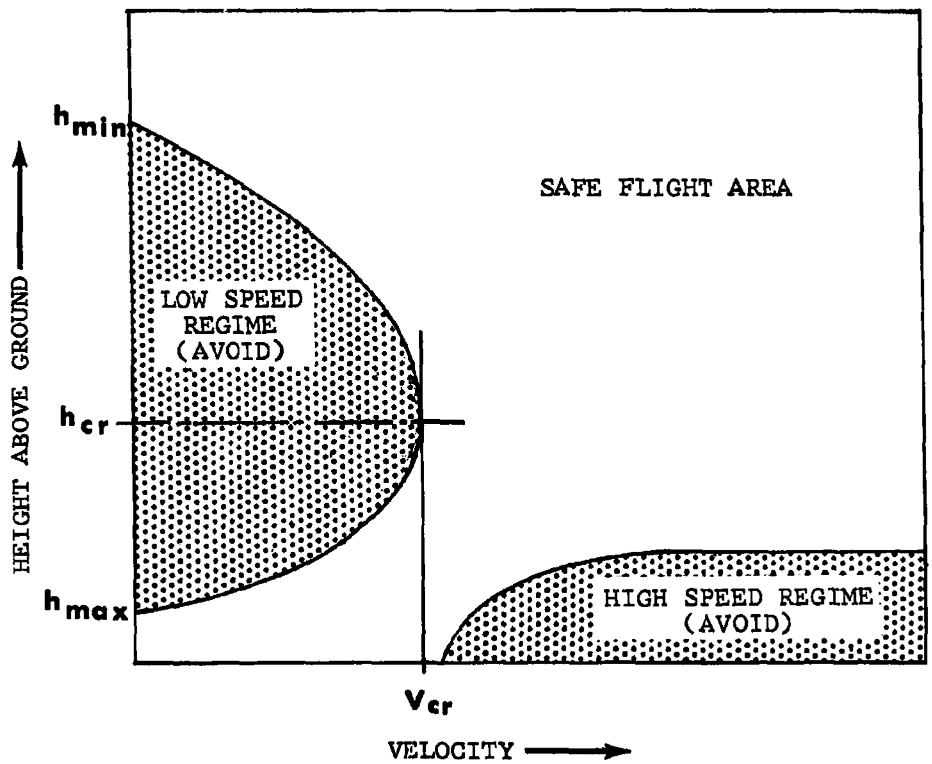

FIG. 1 TYPICAL HEIGHT-VELOCITY DIAGRAM

Helicopter manufacturers during certification processes are required to submit height-velocity diagrams as part of the Aircraft Flight Manual for the models they produce. Such diagrams have, in the past, been based primarily on sea level flight test data. Little quantitative data exists as to the effect of higher operating density altitudes upon these sea level diagrams; hence, the primary reason for this program.

Several theoretical studies have been made of the height-velocity diagram and of the factors that may affect it (references 1, 2 and 3); however, insufficiency of actual flight test data specifically directed toward substantiation of these various considerations has hampered progress. This report presents flight test data which are essential for thorough treatment of the problem.

DISCUSSION

Test Aircraft

The test vehicle was a light weight, single rotor, single engine, helicopter as shown in Figure 2. This aircraft was selected for the height-velocity diagram flight test program because of its ability to perform at altitudes well above the altitude range selected for this investigation. Pertinent specifications of this aircraft are presented in Appendix I.

Test Instrumentation

Airborne and ground instrumentation was utilized to record helicopter performance and meteorological data. Details of the quantitative information measured and the equipment utilized are presented in Appendix I.

Test Operations and Procedures

1. Flight Test Program

The flight test program was conducted at four centrally located test sites in the state of California during the period from September 15, 1962, through November 13, 1962. These test sites selected for their elevation and test environment, were as follows:

Fresno Municipal Airport	Elev.	332 ft. MSL
Bishop Municipal Airport	Elev.	4118 ft. MSL
Long Valley Landing Strip	Elev.	7120 ft. MSL
Coyote Flats Test Strip	Elev.	9870 ft. MSL

FIG. 2 TEST AIRCRAFT

A total of 465 test runs were conducted to determine the height-velocity diagrams at the selected test altitudes for gross weight conditions of 2415 pounds, 2650 pounds, and the maximum certificated gross weight of 2850 pounds.

Following the project flight tests conducted at the above locations, a brief supplementary test program was undertaken at Fort Worth, Texas, 706 MSL, to investigate the effect of increased rotor inertia on the height-velocity diagram.

2. Test Methodology

A schematic view of the test site layout showing the relative locations of the test course, space positioning equipment, central markers, and meteorological equipment used for the flight tests is shown in Figure 3.

The following is a general description of how the tests were conducted:

a. Upper Boundary of the Low Speed Regime

The pilot would fly over the test course at a specific steady airspeed at a conservatively safe height above the ground and execute a simulated power failure by sudden retardation of the throttle to fully disengage the rotor clutch. A one-second delay before rotor pitch reduction was maintained to simulate pilot reaction time to engine failure. From this point, the pilot maneuvered the helicopter to give the best available combination of airspeed, rotor speed, and rate of descent to effect a satisfactory landing. This procedure was repeated at the same airspeed with the height-over-the-ground being progressively reduced, or at the same height with airspeed being progressively reduced, until a maximum performance point was reached. This point was plotted as a point on the H-V diagram which was established when the pilot believed that he could not have made a safe landing without damage to the landing gear if the entry height or airspeed had been lower. The validity of his judgment was verified by means of limited on-site data reduction performed to ascertain entry conditions, touchdown speed, landing load factor, time delay for pitch reduction and to insure that all data had been recorded for final reduction.

b. Low Boundary of the Low Speed Regime

The lower boundary of the low speed regime was established by having the pilot commence his entry trim condition and landing

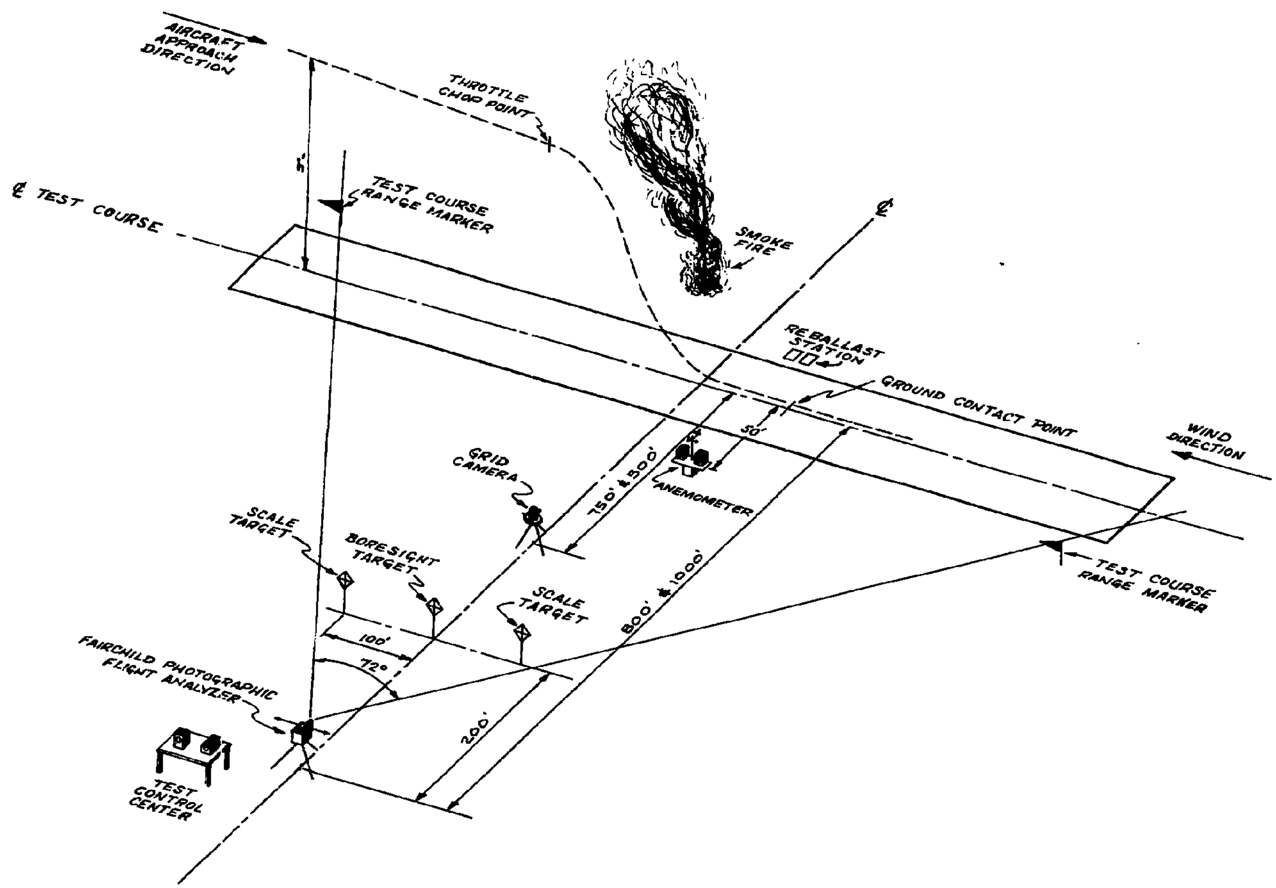

FIG. 3 TYPICAL TEST SITE LAYOUT

execution for the low hover point at a very low height of approximately 2 to 3 feet and subsequently increase his height to a maximum from which he could still execute a safe landing within the established criteria. No specific time delay requirements were imposed, and the pilot essentially used a technique of maintaining his existing collective pitch setting until the required time for full application prior to touchdown. When a point was thus established for the low hover height, the pilot would proceed to progressively higher forward speeds and repeat the process. This sequence continued until speeds and heights approaching the "knee" area were reached.

c. Intermediate Portion or "Knee" of the Low Speed Regime

The intermediate portion of the curve forming the "knee," or outermost extremity, was developed by flying at various constant heights and decreasing airspeed with each subsequent power-off landing until a minimum airspeed for safe landing was reached, as previously discussed in the paragraph concerning the upper boundary.

3. Test Limitations

a. High Speed-Low Height Regime

The high speed regime of the height-velocity diagram is a function of the height loss immediately following power failure (rotor inertia), the height necessary to rotate the helicopter for a flare (tail boom clearance), the ground handling characteristics (landing gear configuration) and the type of terrain (landing surface conditions). Only the height loss following power failure can be considered to be associated with the effects of altitude, while the high speed ground handling characteristics and the condition of the landing surface merely dictate the maximum allowable speed at which it is safe to touchdown. This, in turn, dictates the height above the ground necessary to execute a maneuver to obtain a contact speed at or below the maximum permitted. The test vehicle used in the program had a negligible height loss following power failure, which was demonstrated by making high speed runs as low as four feet above the runway and safely executing simulated power failure landings. In order to establish the effect of altitude on this portion of the diagram, several runs at each of two altitudes were made from a given speed and height above the ground for the purpose of obtaining the minimum contact speed. Presumably higher altitude would require higher touchdown speeds; however, data recorded at Long Valley (7120) feet) and Fresno (sea level) were inconclusive in bearing out this theory.

In general, this realm of flight was not thoroughly evaluated because, among the many factors affecting the magnitude of the high speed regime, altitude is probably of least importance. It was not the intent of this project to explore the effects of the other variables on the height-velocity diagram.

b. Accelerated Climb-Out Regime

The test techniques used in this program for the development of the lower boundary of the low speed regime to the "knee" do not duplicate the techniques used in the development of the H-V envelope for Rotorcraft Flight Manual certification purposes. For certification tests, the aircraft is placed in an accelerated climb condition at the time of simulated engine failure instead of being in steady level flight as used in this program. The steady-state, level-flight approach was chosen for several reasons. Foremost of these is that this technique lends itself to a reasonably high degree of repeatability by eliminating the many variables involved in accelerated climb out which are difficult to control; thus, a more accurate analysis of the altitude effects could be obtained. In addition, instrumentation to provide the pilot with accurate knowledge of his height and airspeed during an accelerated run would necessarily be much more complex than that needed for the steady-state, level-flight technique.

c. Terrain Conditions

The conditions and physical characteristics of the landing surfaces at each of the test sites were somewhat different. At Bishop (4118 feet MSL), the landing strip was smooth blacktop, broad and level, offering excellent landing conditions. Similar conditions prevailed at Fresno (332 feet MSL) with the exception that the landing strip was concrete. At Long Valley (7120 feet MSL) and Coyote Flats (9870 feet MSL), however, conditions were not quite as ideal. The surface at Coyote Flats was hard baked sandy soil overlaying a bed of shale and rock which was not entirely satisfactory for this type of program. At Long Valley, the surface was rough blacktop, very narrow, highly crowned, and had a slight downhill slope in the test site landing area.

4. Test Criteria

a. Rotor Speed

In order to eliminate as many variables as possible, the rotor speed in steady state autorotation at 50 mph CAS was kept constant

by adjusting the low pitch blade angle at each altitude tested. This involved raising the low pitch setting slightly at each test altitude by changing the length of the pitch link. Total collective pitch travel, therefore, was always available for control purposes.

b. Pilot Procedures

There were no restrictions placed on horizontal touchdown velocity; that is, the pilot was not instructed to obtain the minimum touchdown speed nor was he limited as to his maximum touchdown speed. The criterion of a successful landing was the avoidance of landing gear stresses above critical. The specific techniques of handling the helicopter were left to the discretion of the pilot, and a discussion of these techniques can be found under "Pilot's Comments" in Appendix II. The one limitation in technique imposed upon the pilot was the one-second delay to simulate engine failure as previously discussed.

The decision as to whether a landing was a maximum performance effort was made by the pilot. His evaluation was based on whether he believed he had any usable reserve energy remaining in the form of rotor speed (collective pitch) or airspeed (flare). Thus, on several occasions, extremely hard landings were discounted by the pilot because, in his opinion, the landings were a result of poor technique or execution, whereas he actually had energy left with which to recover. These runs were generally repeated until the pilot was satisfied that a maximum performance point was obtained.

c. Weight Control

Weight was kept within approximately $\pm$ 1/2 percent by adding ballast after every few runs and refueling as required.

d. Wind Allowables

Limitations were placed on allowable wind velocities for these tests. These wind velocities were measured at a 12 ft. instrumentation height. Hovering and very slow speed tests were not conducted in wind velocities in excess of 2 mph, and all other tests were discontinued when the wind exceeded 5 mph at this height. Tests were generally conducted when a headwind existed. Only the down-runway component was used for entry speed computations. Occasionally, however, flight tests were conducted with a slight tail wind due to the necessity of having the rising sun at the pilot's back in order to minimize distracting glare.

e. Altitude Control

While the prime purpose of the program was to determine the effects of altitude on the H-V diagram, it was considered that, in view of all of the other variables involved, small variations in density altitude at the test site would have little effect on the test data results. Further, since wind was the most critical item with respect to continued testing, some latitude in density altitude was allowed for any given weight at each test site. All weights at each site were tested over a common range of density altitude which was within approximately 600 feet of the average density altitude.

f. Entry Speeds and Conditions

All speeds used in the program and in this report are given in terms of calibrated airspeeds (CAS). The rotor rpm was held constant over the altitude range also in accordance with a common calibrated airspeed of 50 mph. The calibrated entry airspeed used for each point on the H-V diagram was obtained from the photographic record as ground speed and converted to calibrated airspeed.

Difficulty was experienced in obtaining entry speeds below 20 mph. This was particularly critical at the higher heights above the ground, where it was extremely difficult for the pilot to judge airspeed without close ground reference. Below 20 mph the airspeed indicating system of the helicopter became erratic because of downwash, and it was impossible for the pilot to ascertain and make minor incremental adjustments in airspeed. A car pace was used for approximate airspeed indication with some degree of success at the low heights but this method was less satisfactory for very high heights above the ground.

The altimeter was generally satisfactory in providing the pilot with height information at the high height entries but was less effective at the low heights above the ground, where close tolerances in height were required. Here the pilot used various ground references plus monitoring from the ground crew for height information, which was not very precise.

ANALYSIS AND RESULTS

Height-Velocity Diagrams

Height-velocity curves were first faired through the test data. Various kinds of cross-plots were then constructed and studied to determine what kind of relationships, if any, did exist. Information from these cross-plots was then replotted along with the original data, and the original height-velocity curves were adjusted to provide the best fit to the cross-plotted points. Generally, the adjusted curves were quite close to the original curves, and most of the differences could be attributed to the vagaries of curve-plotting. The adjusted curves, with experimental data points, are shown in Figures 4 through 14. The variation with altitude for several weights of these adjusted curves is shown in Figures 15 through 17 and for variations in weight at several altitudes in Figures 18 through 21.

An average density altitude was selected for each site for the above diagram plotting process by averaging the altitudes of the test points. While this approach is admittedly not precise, in general, points which were above the average density altitude fall outside the diagrams and points below the average fall inside the diagrams.

Every data point which was not reasonably close to the adjusted curves was analyzed by study of the conditions and time history of the run involved. Sample time histories are shown in Appendix III, and the conditions for each data point are tabulated in Appendix IV. In most cases valid reasons were found which would have justified moving the point toward the curve; however, it was not possible to apply quantitative corrections. There were two general situations where the data points did not fall on the curves within the normal scatter band. One of these was at the 2650 pounds gross weight condition at the 4500 foot altitude, and the other was at 2415 pounds at sea level. Both of these exceptions can be explained in a general way and substantiated by the above analysis. The 2650 pound data, which was obtained at Bishop during the first few tests of the program, falls outside the diagram. This is attributed to conservatism of the pilot in identifying maximum performance during this initial stage of the program. The data at sea level at 2415 pounds shows more than normal scatter, and here it is believed that the combination of light disc loading together with the initiation of the first sea level tests played a large part in producing this scatter. In addition, the test site location at Fresno frequently required that tests be conducted in an indicated tail wind condition, which at the high hover heights could have been completely different

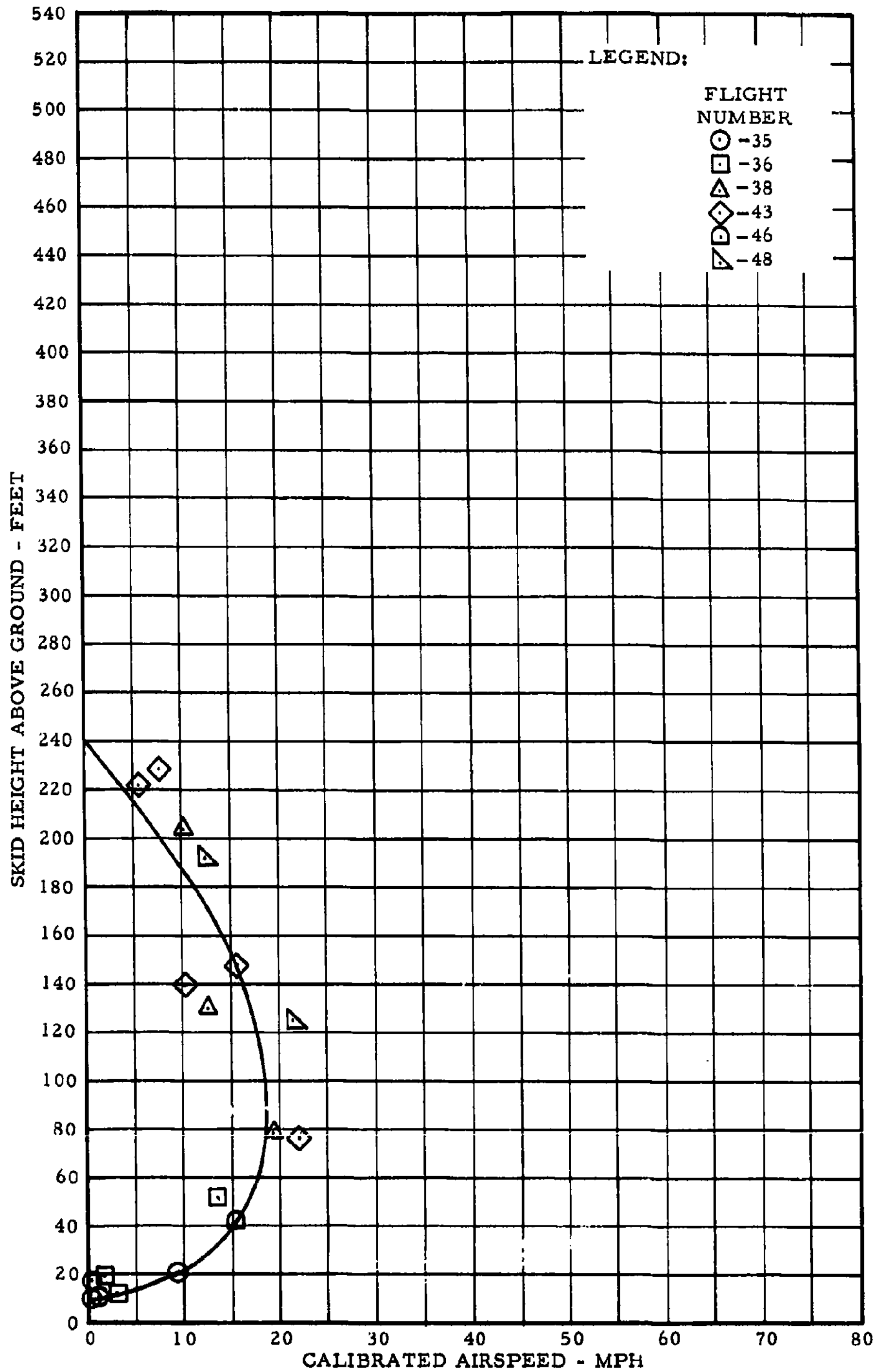

FIG. 4 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2415 POUNDS
AVERAGE DENSITY ALTITUDE 200 FEET

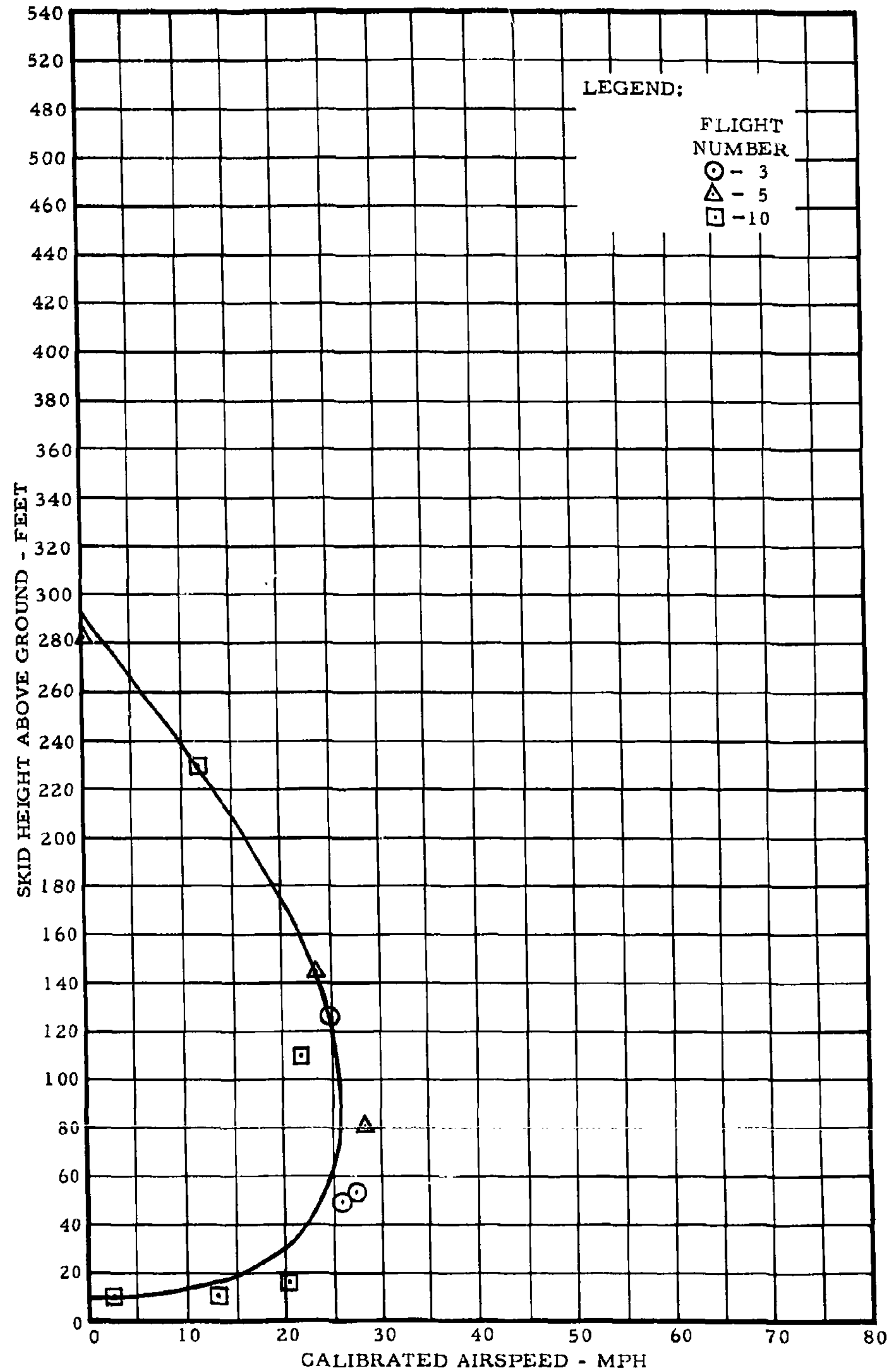

FIG. 5 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2415 POUNDS
AVERAGE DENSITY ALTITUDE 4500 FEET

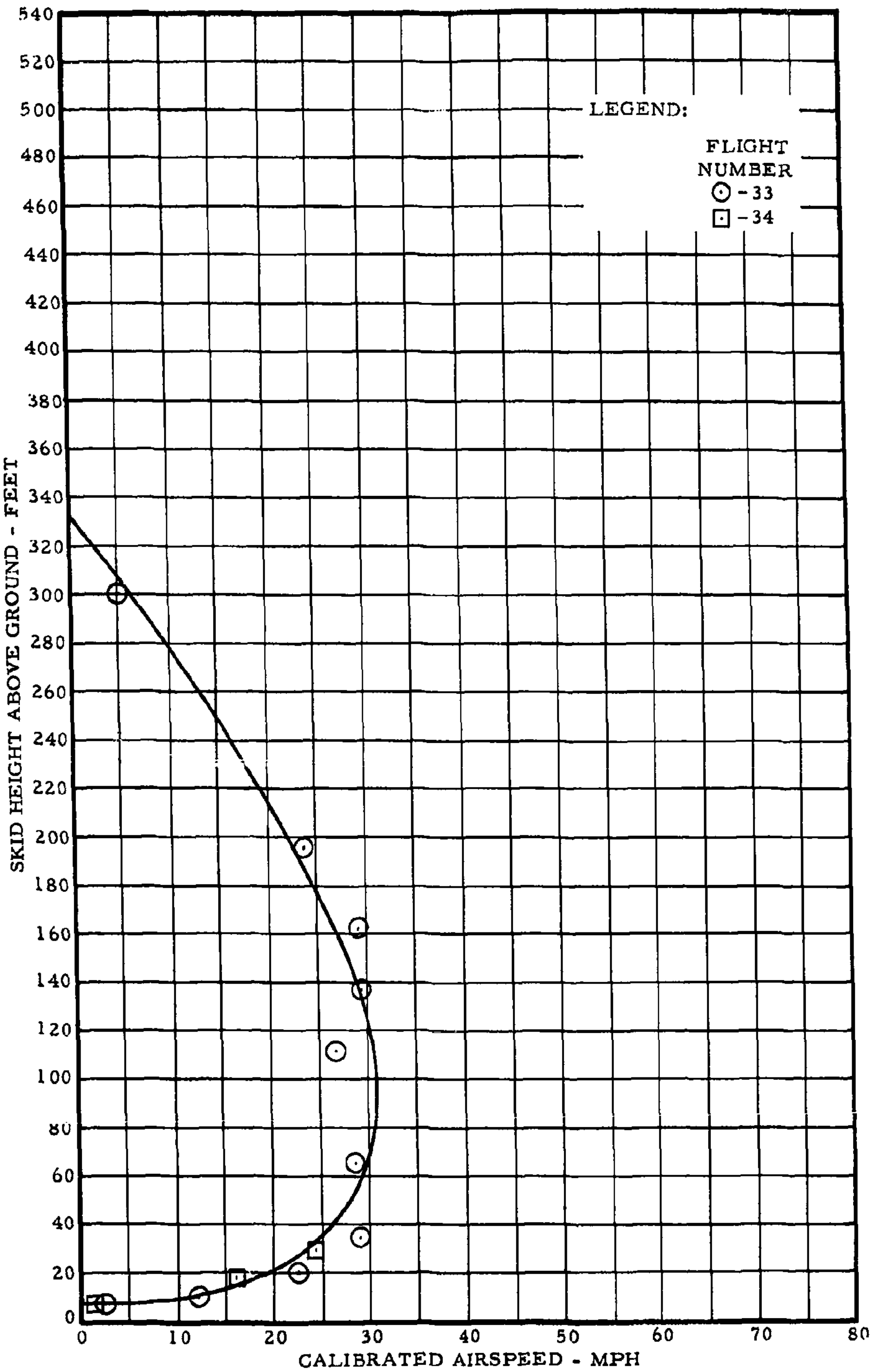

FIG. 6 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2415 POUNDS
AVERAGE DENSITY ALTITUDE 7350 FEET

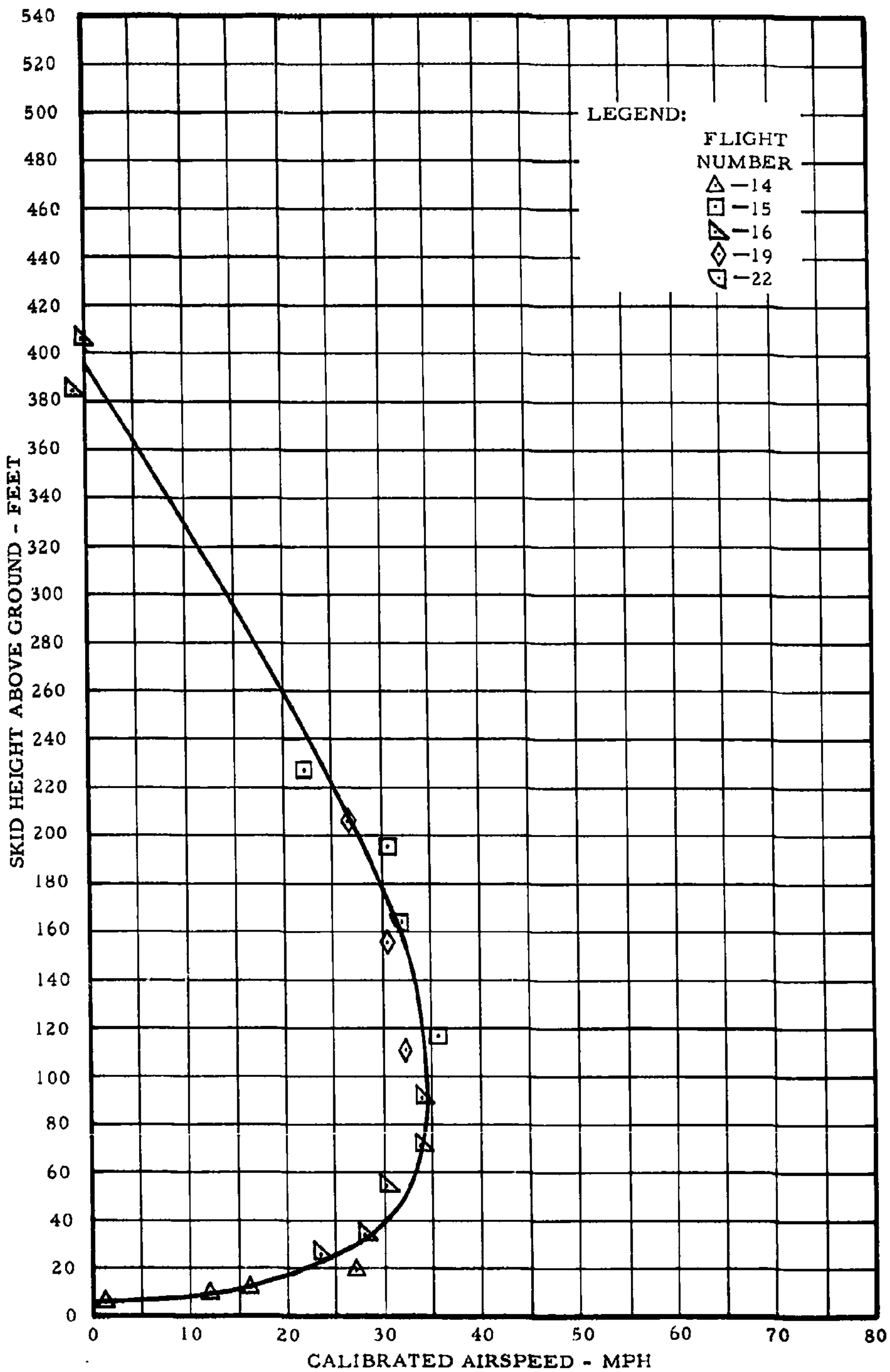

FIG. 7 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2415 POUNDS
AVERAGE DENSITY ALTITUDE 10250 FEET

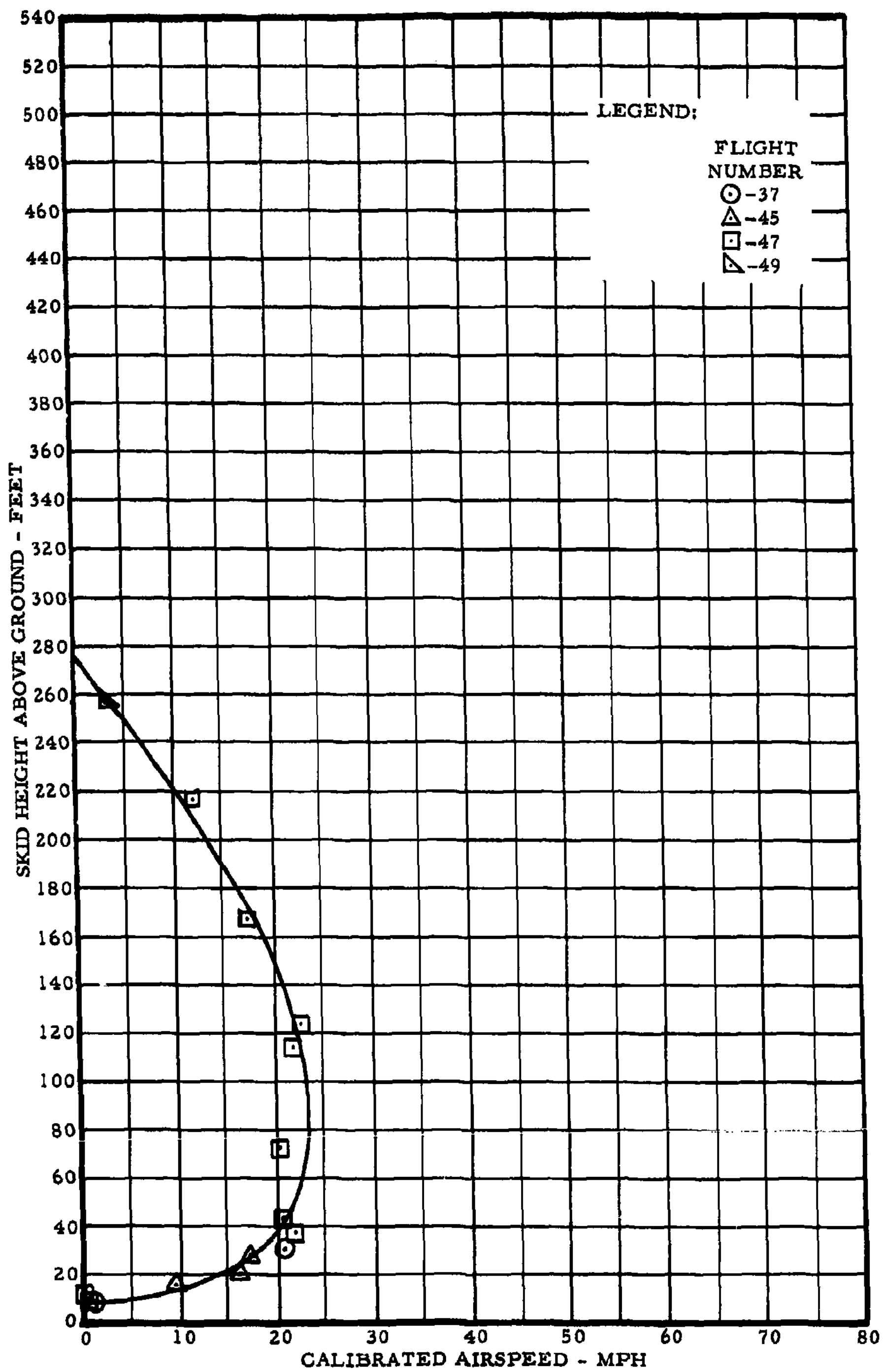

FIG. 8 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2650 POUNDS
AVERAGE DENSITY ALTITUDE 200 FEET

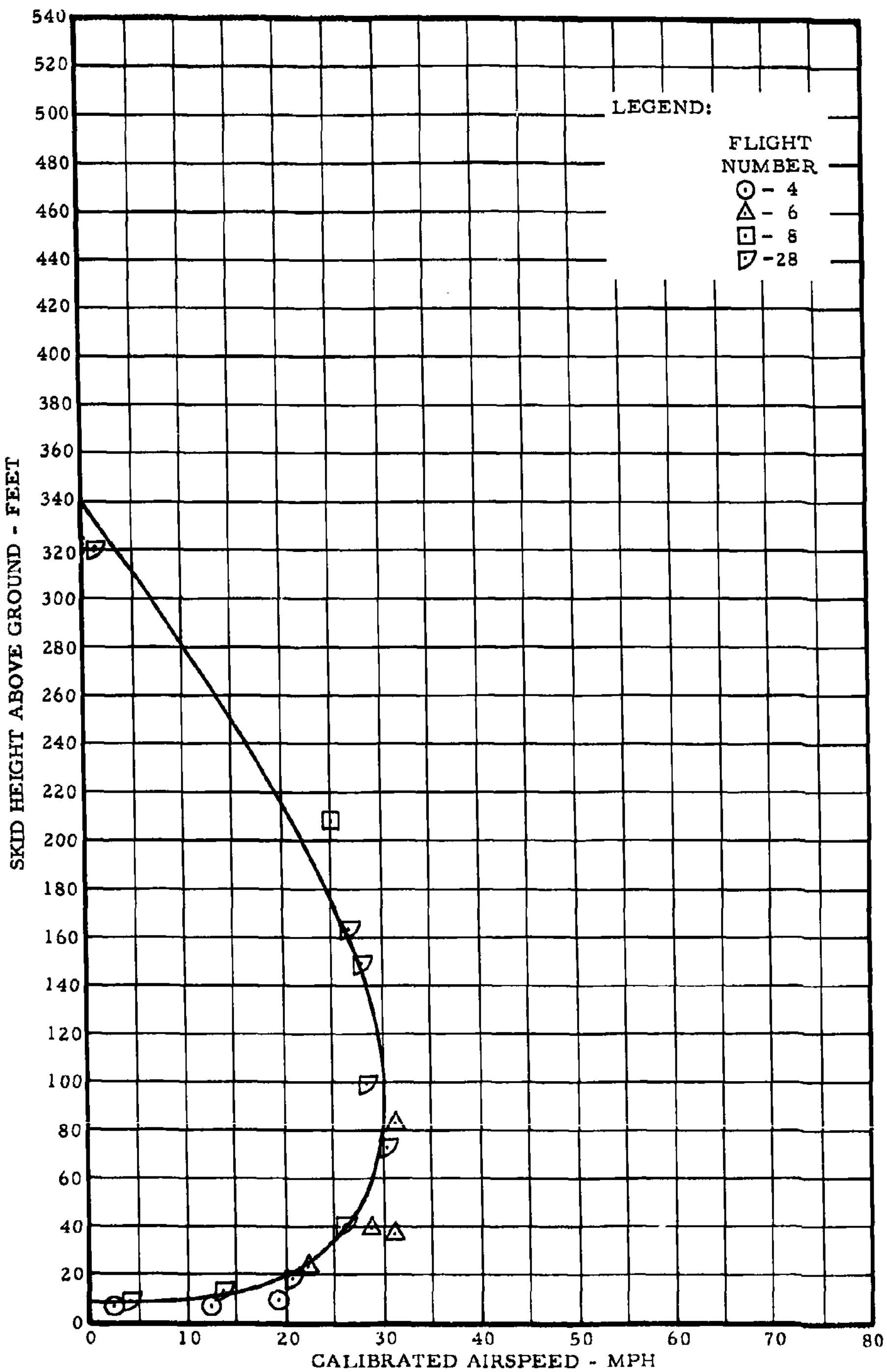

FIG. 9 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2650 POUNDS
AVERAGE DENSITY ALTITUDE 4500 FEET

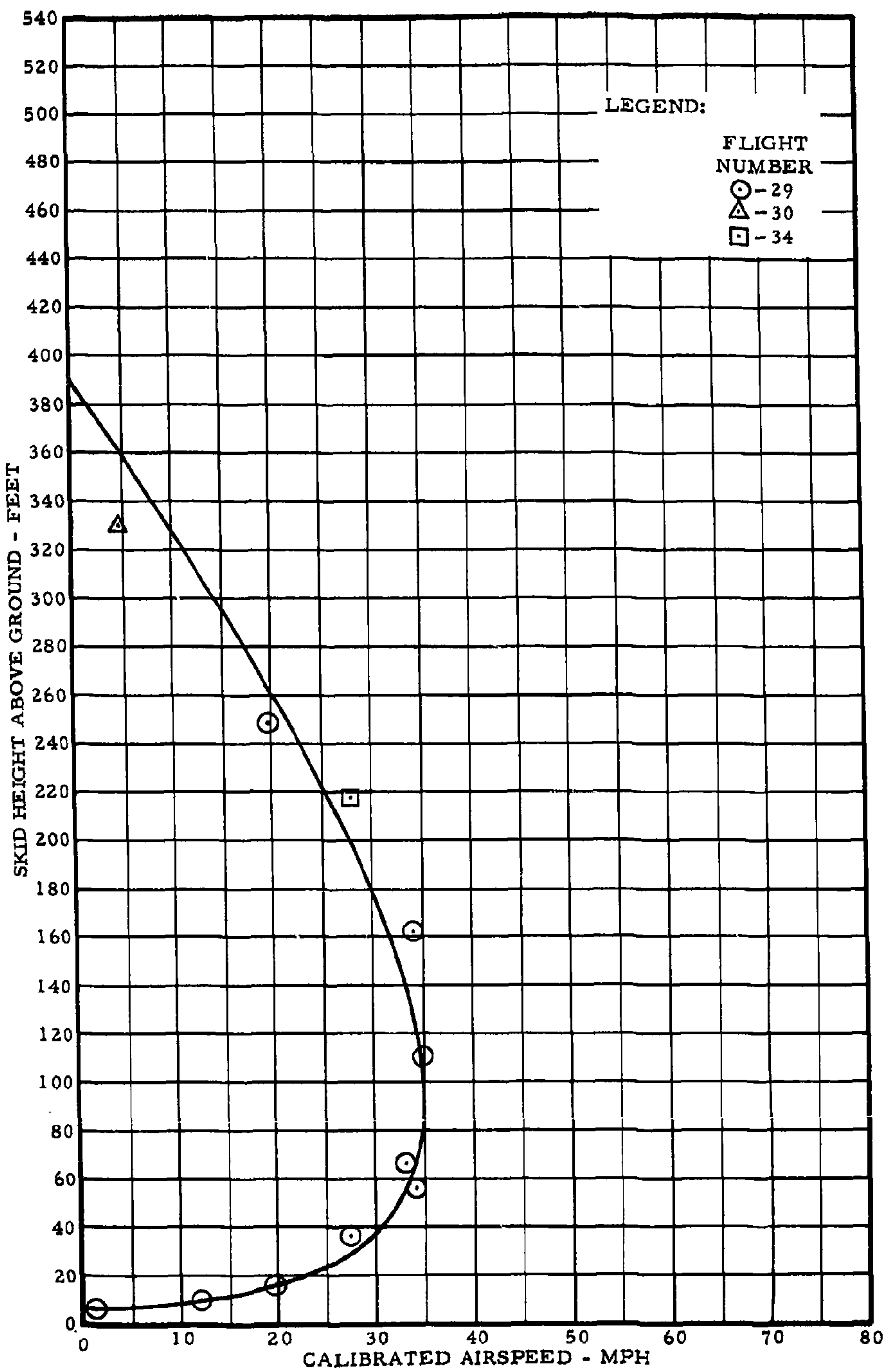

FIG. 10 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2650 POUNDS
AVERAGE DENSITY ALTITUDE 7350 FEET

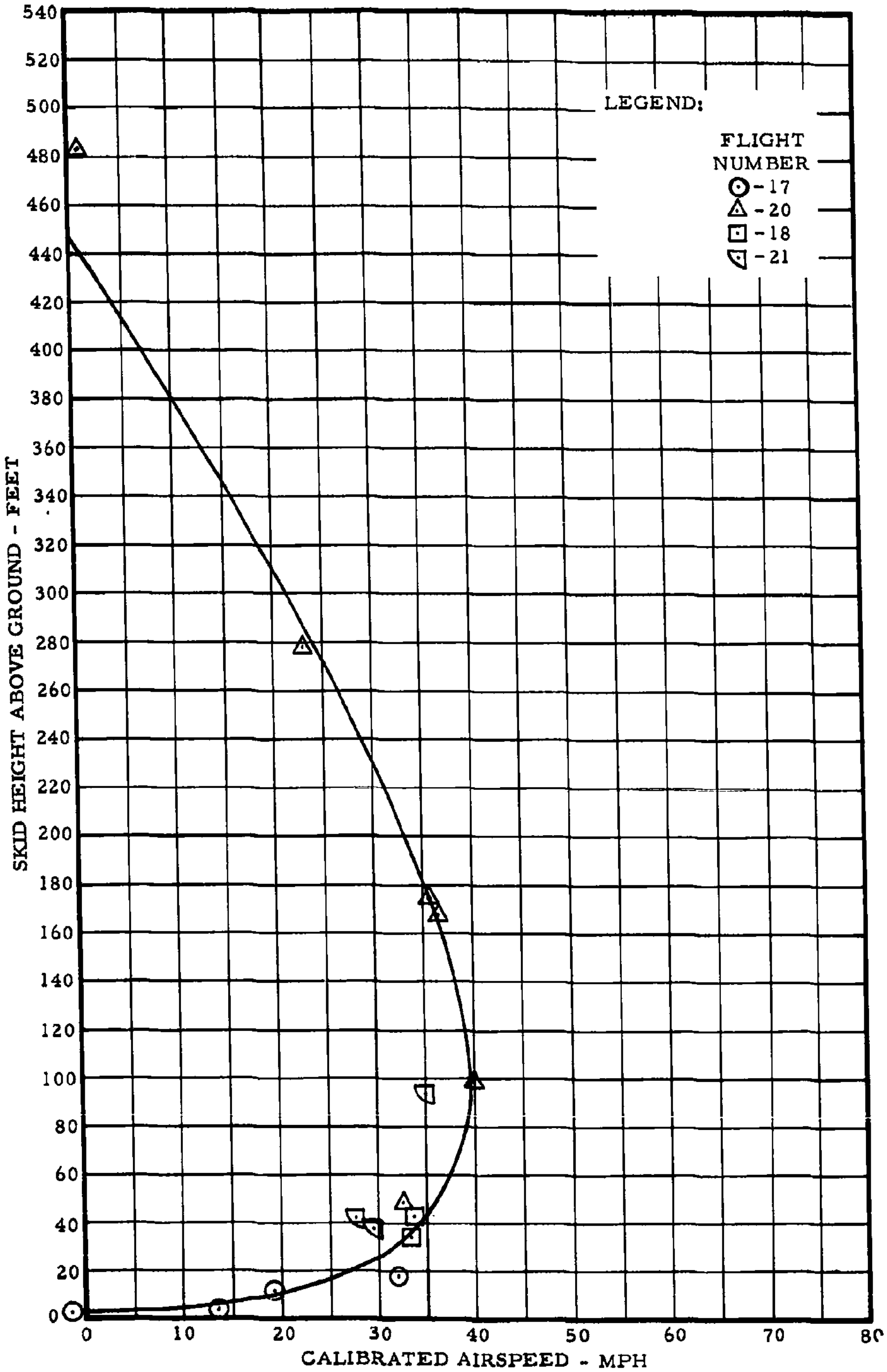

FIG. 11 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2650 POUNDS
AVERAGE DENSITY ALTITUDE 10,250 FEET

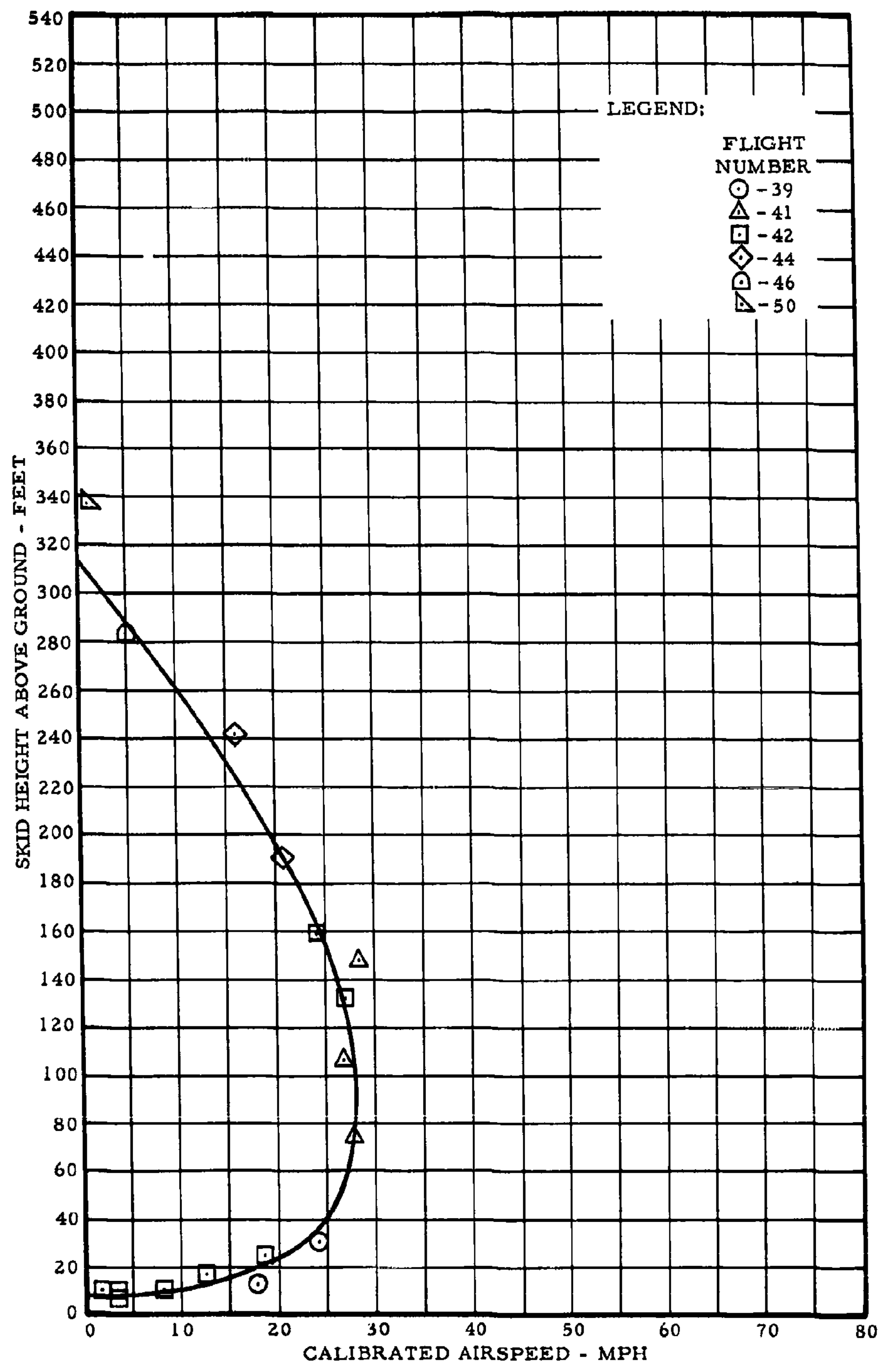

FIG. 12 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2850 POUNDS
AVERAGE DENSITY ALTITUDE 200 FEET

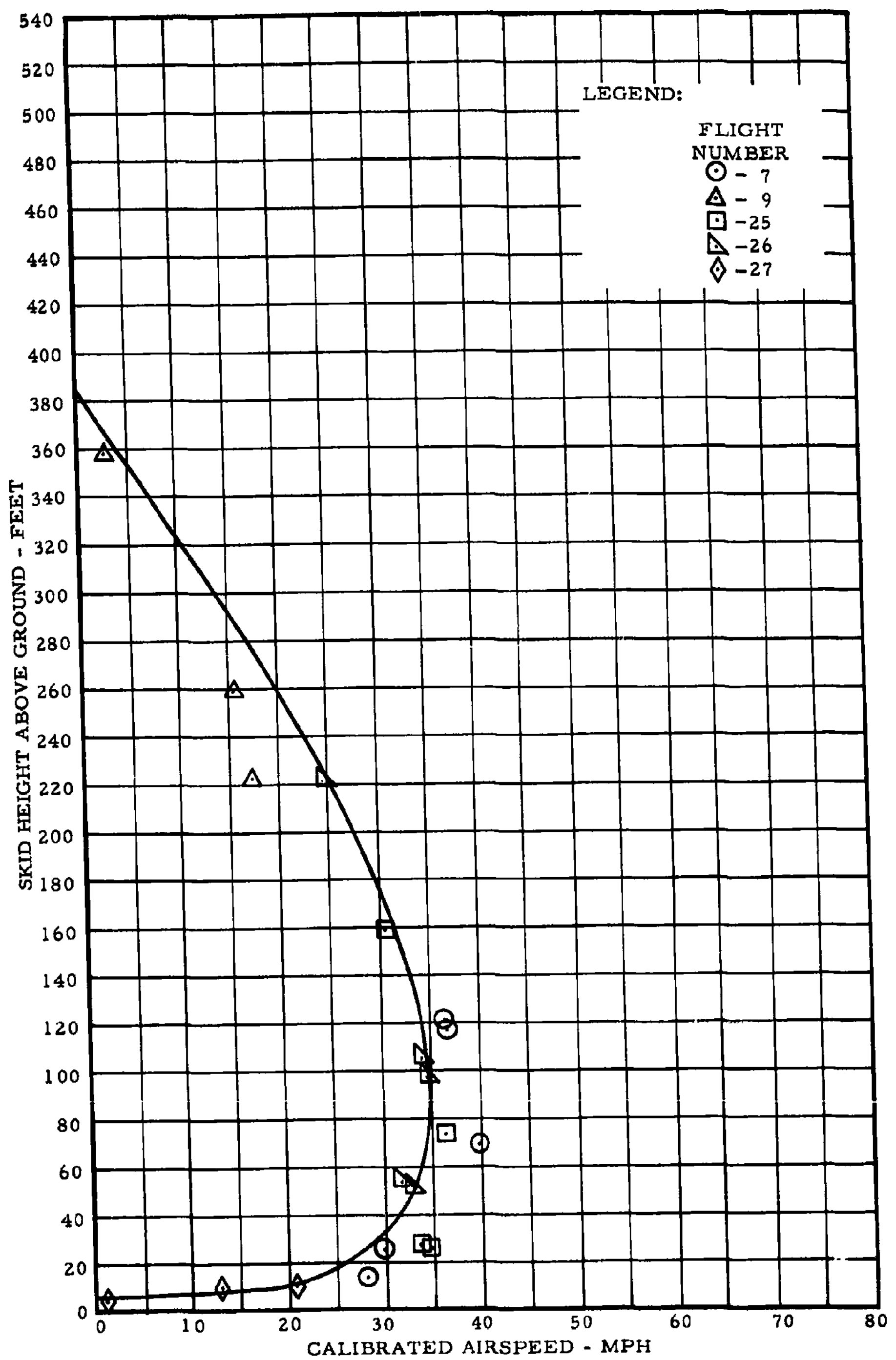

FIG. 13 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2850 POUNDS
AVERAGE DENSITY ALTITUDE 4500 FEET

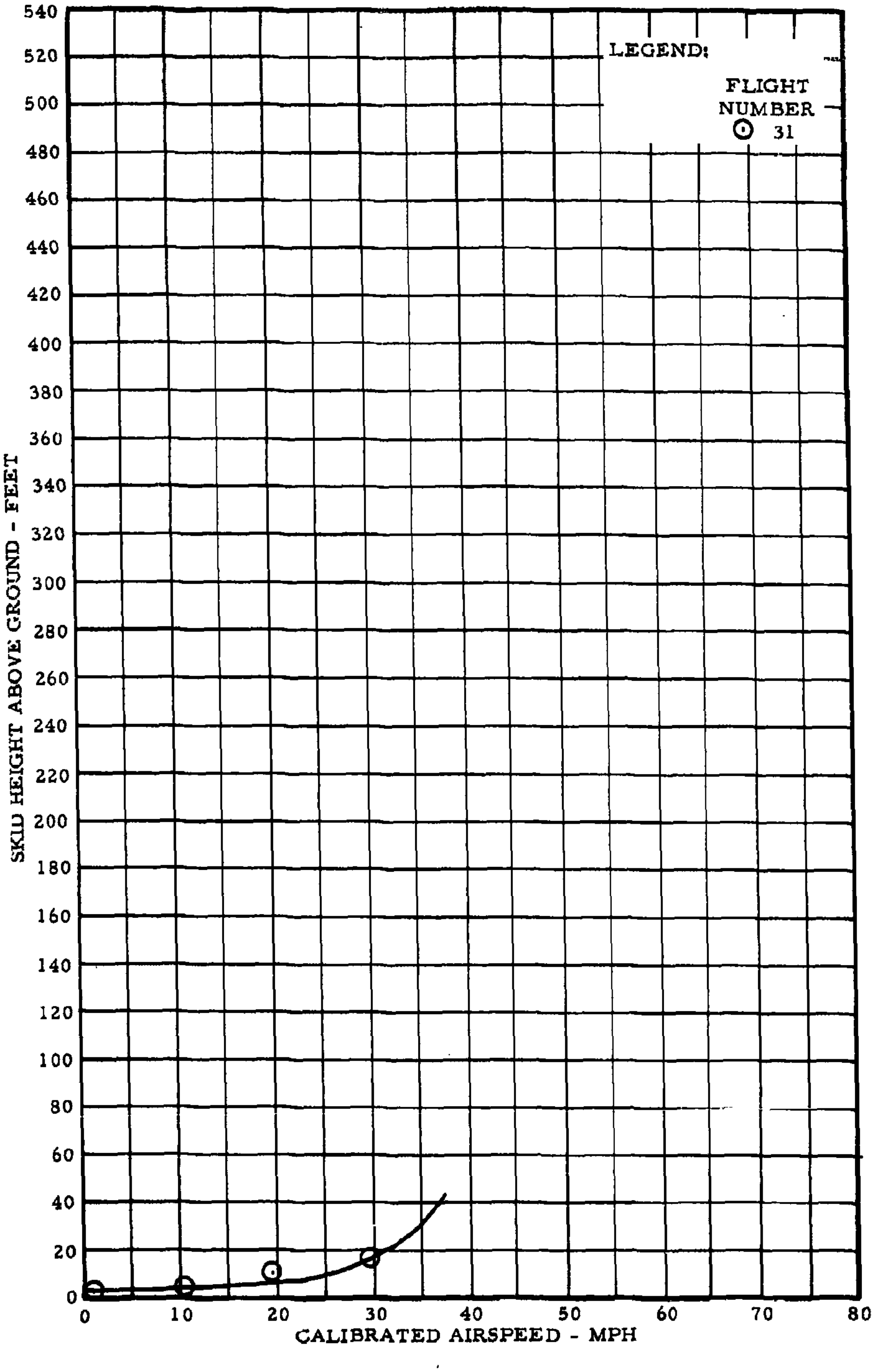

FIG. 14 HEIGHT-VELOCITY DIAGRAM - BASIC DATA
HELICOPTER GROSS WEIGHT 2850 POUNDS
AVERAGE DENSITY ALTITUDE 7350 FEET

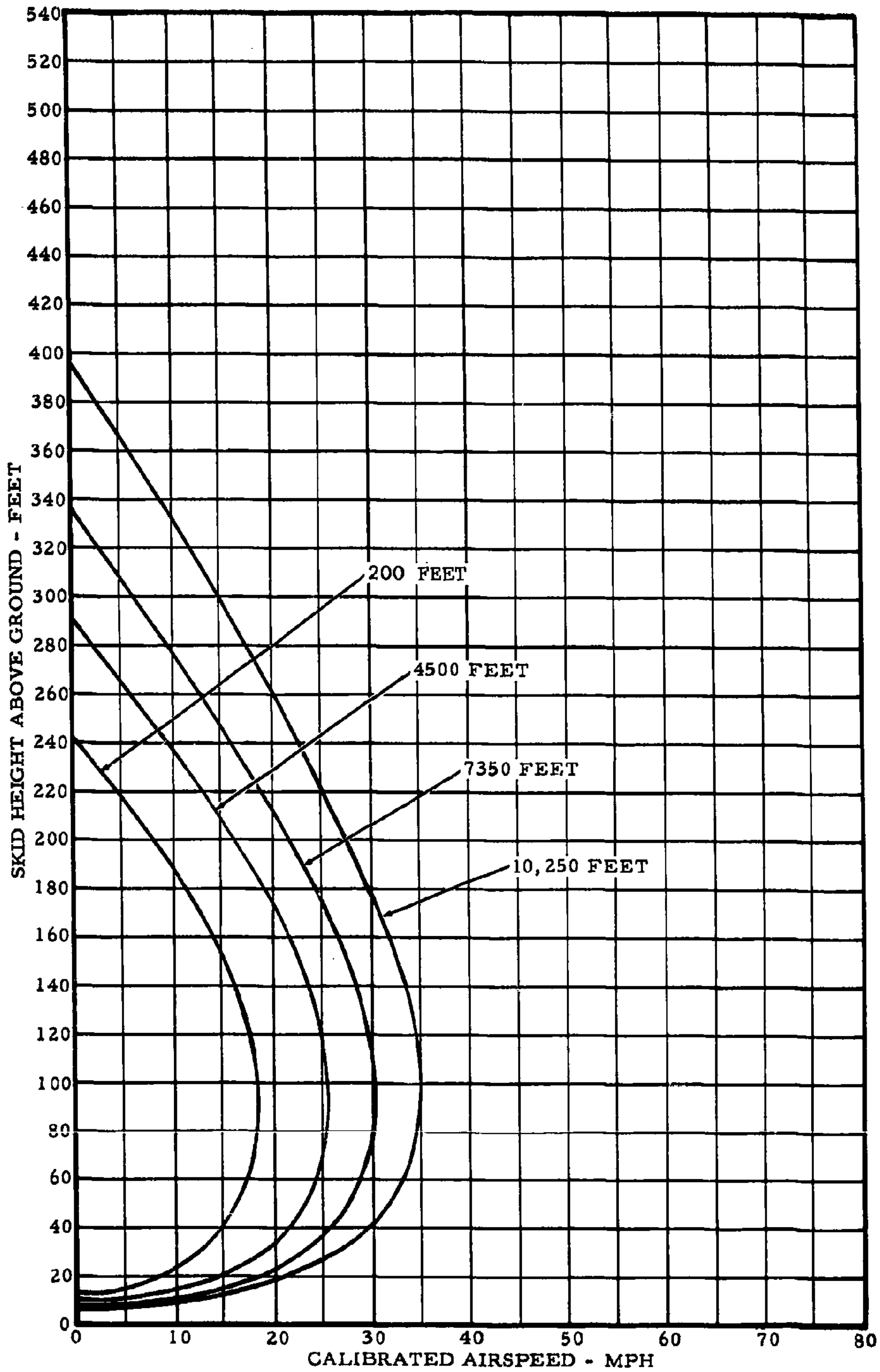

FIG. 15 HEIGHT-VELOCITY DIAGRAM VARIATION WITH ALTITUDE
GROSS WEIGHT 2415 POUNDS

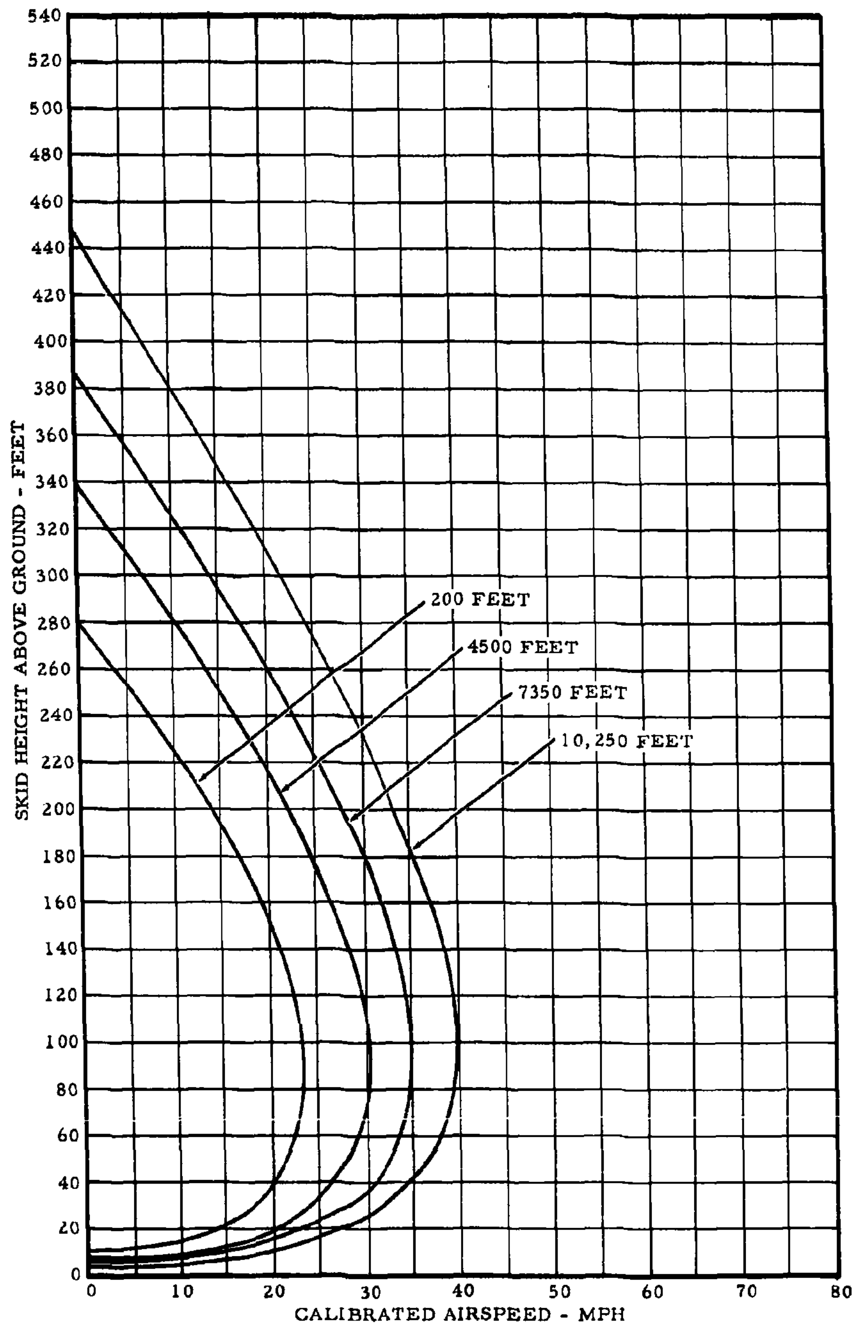

FIG. 16 HEIGHT-VELOCITY DIAGRAM VARIATION WITH ALTITUDE
GROSS WEIGHT 2650 POUNDS

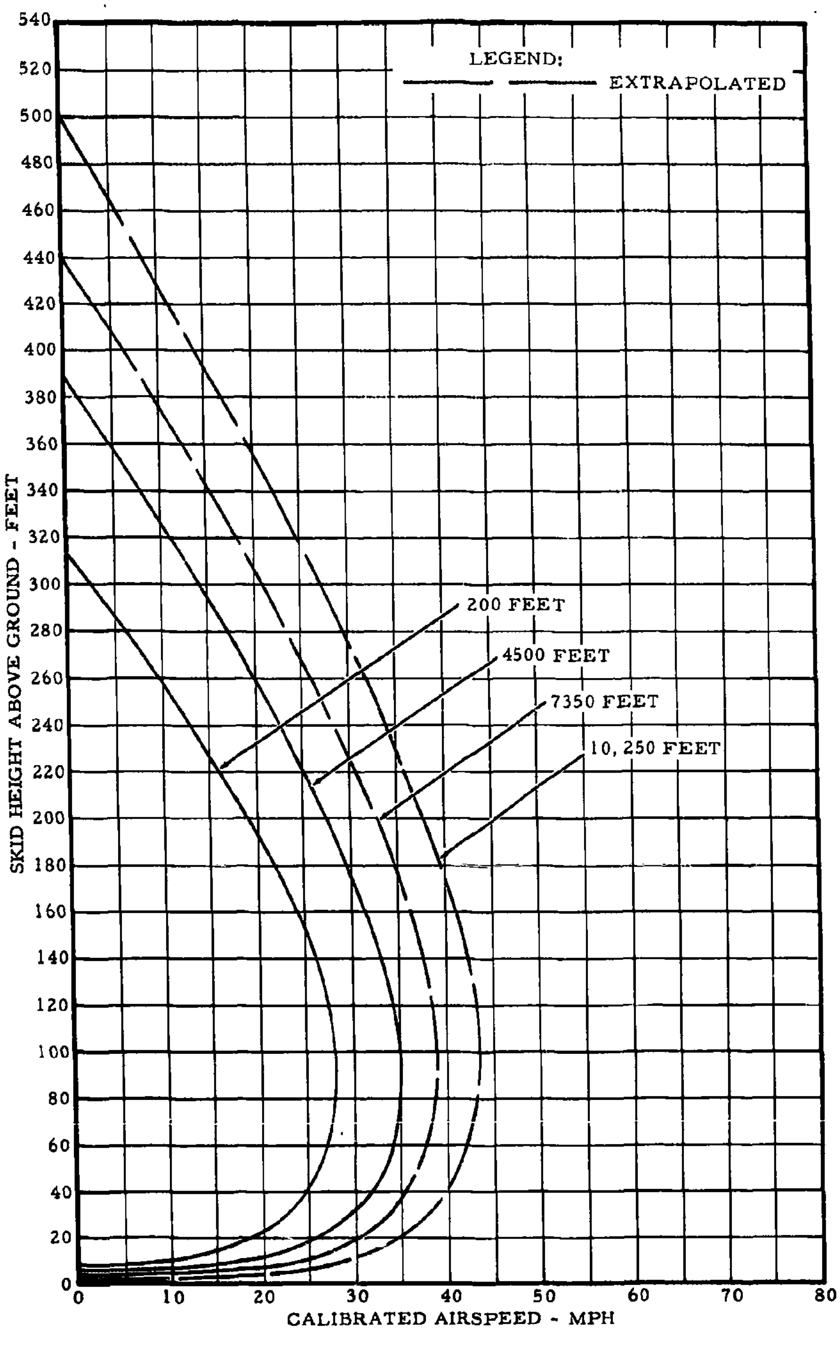

FIG. 17 HEIGHT-VELOCITY DIAGRAM VARIATION WITH ALTITUDE
GROSS WEIGHT 2850 POUNDS

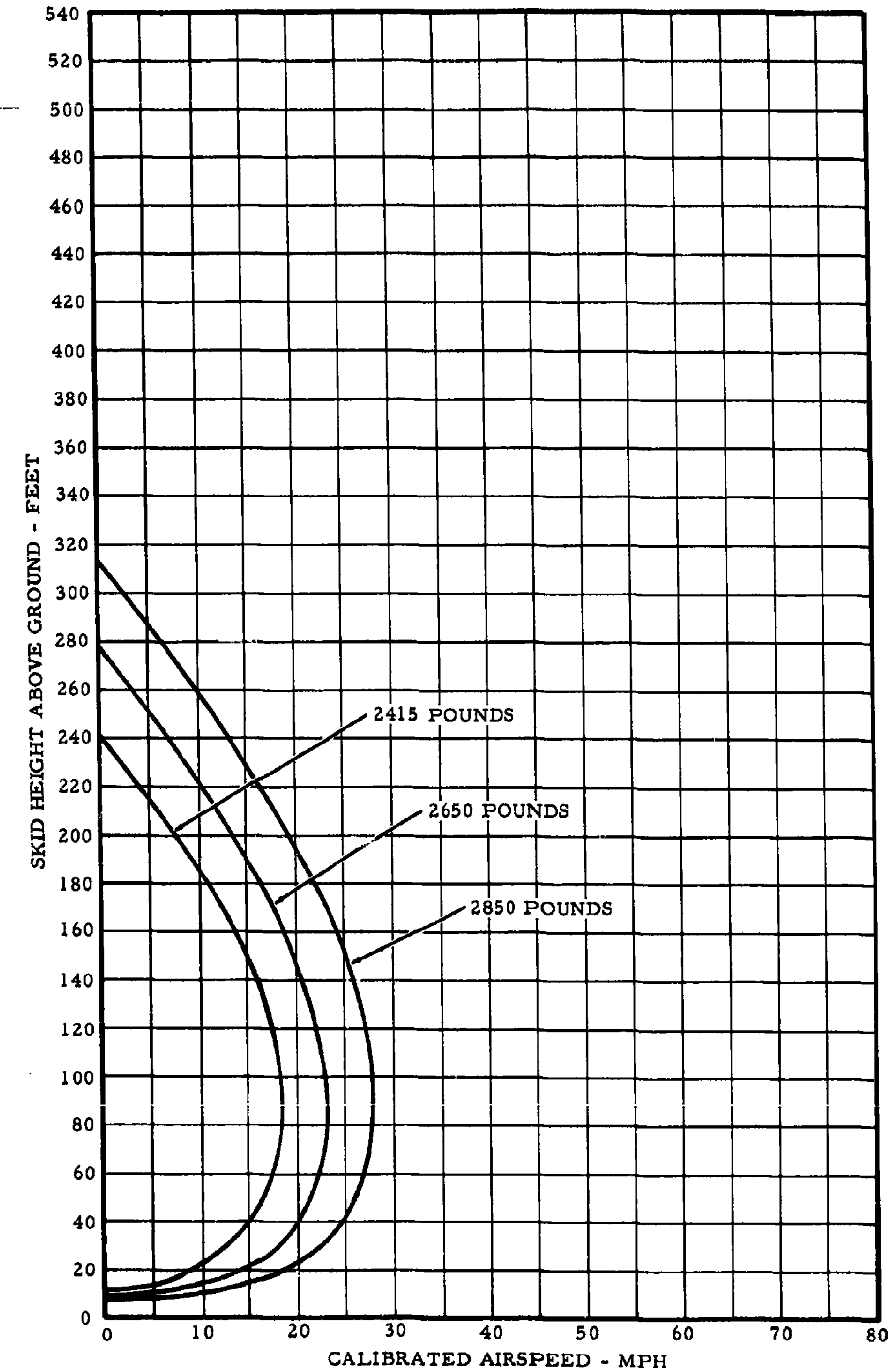

FIG. 18 HEIGHT-VELOCITY DIAGRAM VARIATION WITH GROSS WEIGHT AVERAGE DENSITY ALTITUDE 200 FEET

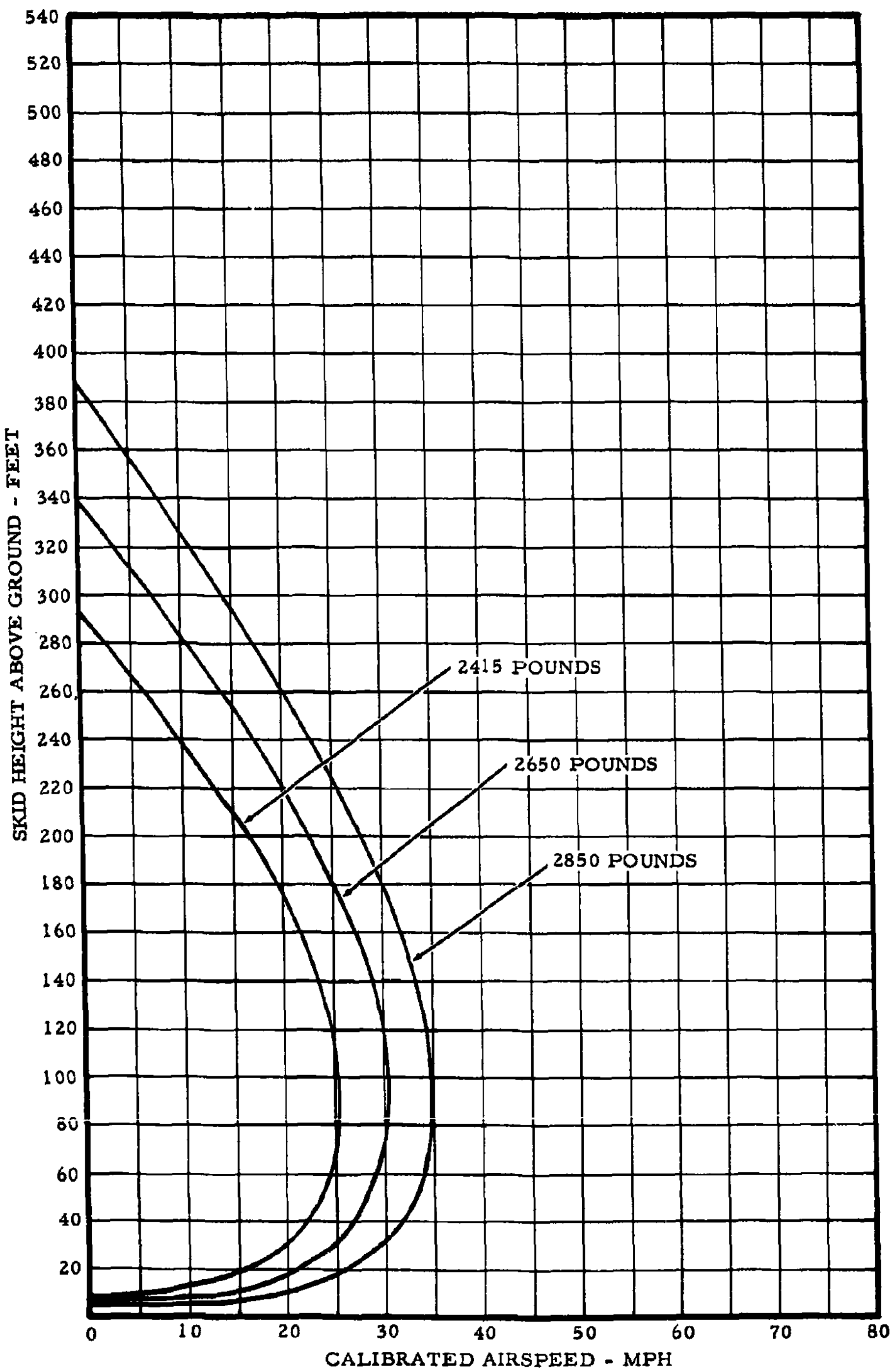

FIG. 19 HEIGHT-VELOCITY DIAGRAM VARIATION WITH GROSS WEIGHT AVERAGE DENSITY ALTITUDE 4500 FEET

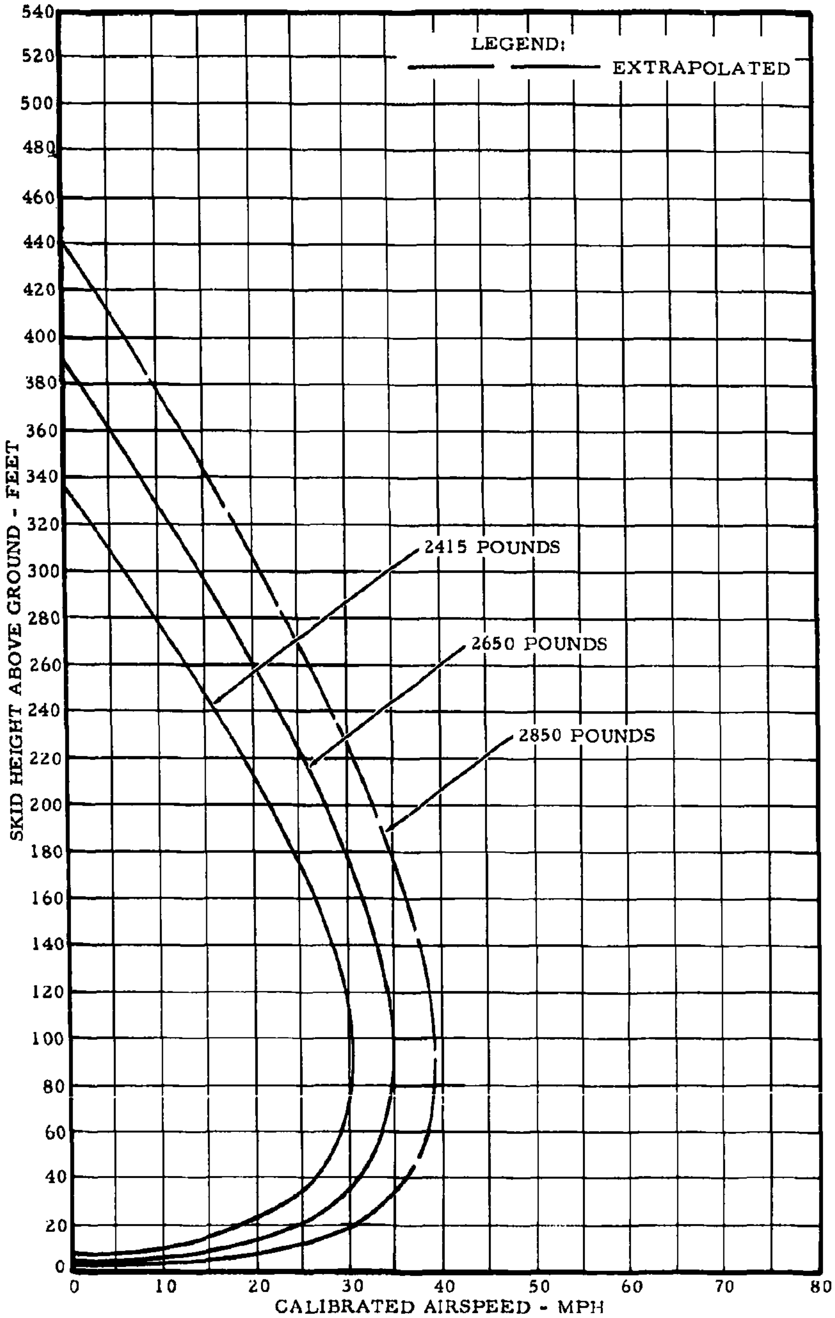

FIG. 20 HEIGHT-VELOCITY DIAGRAM VARIATION WITH GROSS WEIGHT AVERAGE DENSITY ALTITUDE 7350 FEET

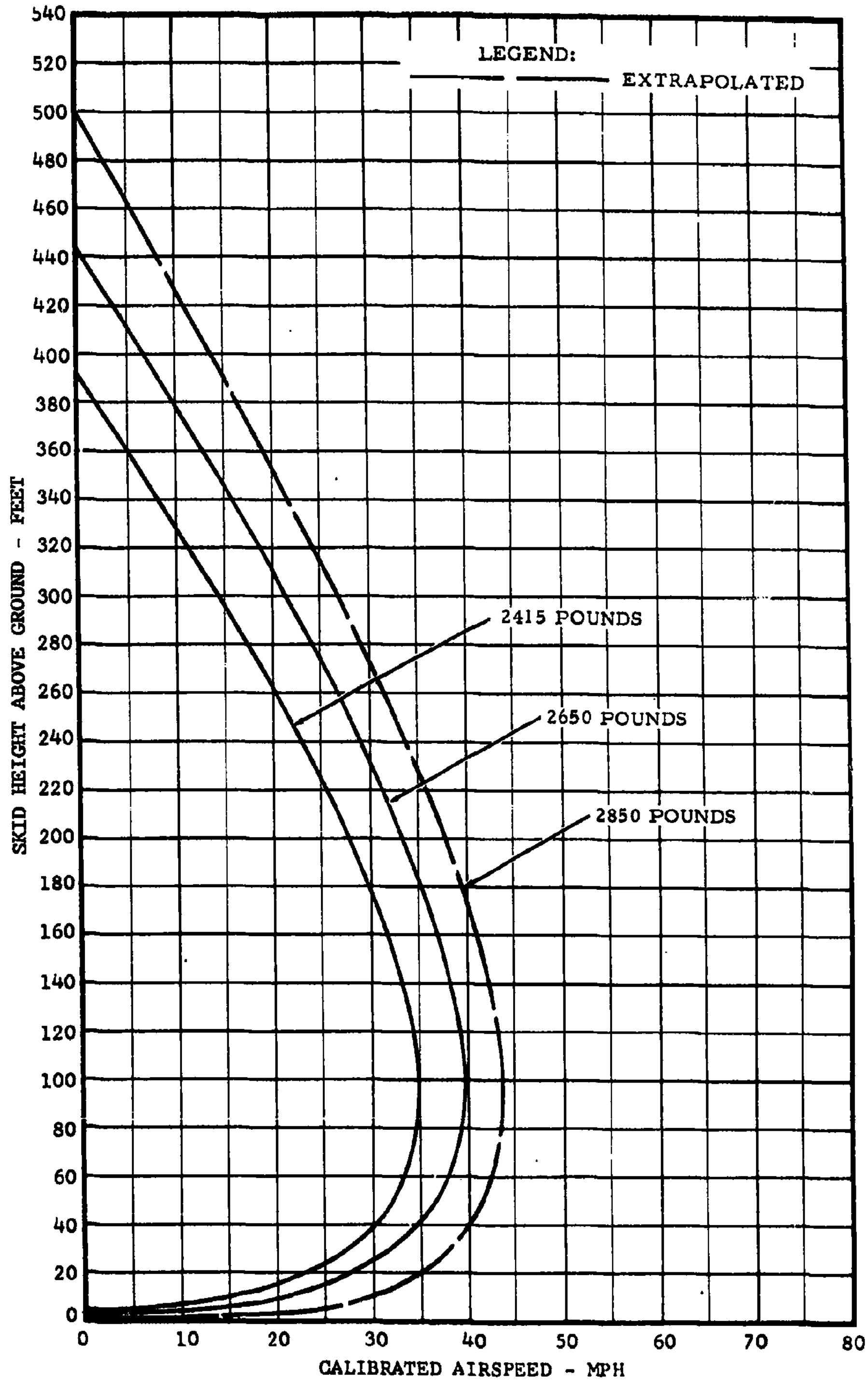

FIG. 21 HEIGHT-VELOCITY DIAGRAM VARIATION WITH GROSS WEIGHT AVERAGE DENSITY ALTITUDE 10,250 FEET

from that measured on the ground. A tail wind could produce much greater variation in a test point than an equal headwind. This is because after power failure the pilot must gain airspeed to zero mph first and then proceed to gain airspeed for the landing maneuver.

Of all the data taken, the greatest variation occurred in the high hover and at the very-high height, slow-speed points. This is a result of several factors, paramount of which was the wind. Wind at altitude was assumed for purposes of data plotting to be equal to the measured wind at the 12-foot height, and this, of course, is problematical. Another factor was that a few percent change in the entry height and a few miles per hour speed differential from zero would make a point appear unsatisfactory when plotted, while in actual practice the ability to make the landing was not appreciably affected. This magnitude of error or variation, when occurring in the vicinity of the "knee" of the diagram, would have the opposite effect - it might look well when plotted, but would be discernible by the pilot during the test. Consequently, in the area of the "knee" it can be said that excellent correlation was obtained and that cross plotting was consistent for heights well above and below h_{cr}. Identical slopes for plots of velocity versus weight or height were obtained at approximately $\pm$ 50 feet from h_{cr}.

An examination of the data relative to specific points provided general information as well as establishing the validity of the particular points being investigated. This data is contained in Table I, which is a summary chart of pertinent facts relative to all of the high hover and near high hover points taken from the time histories. The touchdown speeds (V_{TD} calibrated) appear to be of the same order of magnitude independent of altitude and weight when the entry is approximately at high hover. As the entry speeds increase, the touchdown speeds appear to increase as a function of the entry speed. In most instances where touchdown speed was higher than usual, and where the period from maximum nose-up to touchdown (t_4) was short, the rotor speed was also high. This indicated that available rotor energy was not utilized and that airspeed was substituted for rotor energy.

From this study of the time histories, it was observed that along the upper boundary of the low-speed regime, especially in the vicinity of the high hover points, minimum load factors were achieved when "up" collective was initiated 4 to 5 seconds prior to touchdown, and cyclic flare was initiated so that the maximum pitch angle occurred approximately 3 seconds prior to touchdown. Also, it appeared that it was better to apply collective too soon and hold it than to apply it abruptly just prior to touchdown. It was further noted that a slow steady increase at the rate of 2 degrees per second was more effective

TABLE I

SUMMARY OF HIGH HOVER (h_{min}) AND NEAR HIGH HOVER DATA

FLIGHT NO.	RUN NO.	G. W. (1) pounds	H_D(2) feet	t_1(3) sec.	A_1(4) Δ g	V_D(5) ft/min	t_2(6) sec	t_3(7) sec.	Ω_1(8) rad.	t_4(9) sec.	V_{TD}(10) mph	Ω_2(11) rad.	A_2(12) g	V_{TC}(13) mph
43	10	2427	-100	0.57	-.65	2450	2.55	4.30	33.0	2.8	17.3	28.5	.30	7.9
*43	13	2418	100	0.37	-.60	2460	2.60	3.80	33.0	2.5	16.7	27.0	.90	5.5
* 5	10	2424	5130	0.53	-.75	2680	7.10	4.00	35.5	3.5	10.5	25.0	.70	0.0
*33	20	2397	8100	1.10	-.70	2880	4.00	4.50	36.0	3.0	18.4	29.0	.30	-2.1
*16	10	2408	9520	1.00	-1.00	3380	6.50	5.30	36.5	3.8	17.6	25.0	1.10	-1.3
*16	9	2414	9520	1.60	-.90	3500	4.30	6.30	36.0	4.9	19.7	28.0	.55	-0.5
38	11	2400	200	0.31	-.60	2320	2.80	3.00	34.0	1.8	19.4	31.0	1.30	10.1
10	7	2419	4500	1.32	-1.15	2880	5.60	4.20	34.0	3.5	17.5	26.0	.20	11.7
15	12	2425	10600	0.84	-.80	2460	2.90	6.00	34.5	4.0	23.6	25.0	.50	22.0
*49	2	2649	-140	1.20	-.80	2820	12.50	4.00	32.0	2.0	18.8	27.0	1.00	3.4
*28	25	2635	5010	1.20	-.75	3140	3.50	5.00	35.5	4.0	19.4	26.5	.65	0.7
*30	9	2638	7150	1.10	-.75	3210	5.60	6.00	37.0	3.5	19.0	30.5	.30	4.1
*20	14	2650	11150	1.50	-.70	4125	4.50	4.80	37.3	3.3	16.1	29.0	.10	3.0
*20	15	2642	11150	1.50	-.70	3620	6.40	1.50	37.0	1.5	21.1	32.5	3.1**	0.8
47	12	2544	450	0.85	-.50	2400	4.10	4.60	35.0	3.1	20.3	27.5	.45	11.9
29	18	2636	8180	1.00	-.75	3230	3.90	5.30	34.0	3.3	28.1	29.5	.75	19.7
20	13	2654	11100	1.40	-.75	3320	4.60	4.75	34.0	2.5	25.6	32.0	.65	23.3
*50	1	2855	100	0.50	-.70	3010	4.75	4.80	33.0	3.6	17.5	26.0	.50	1.0
* 9	5	2816	4450	1.00	-.85	3105	4.90	5.30	36.5	3.8	20.4	26.0	.40	2.7
*46	10	2839	-30	0.90	-.70	2650	3.00	4.00	36.5	3.0	20.7	29.5	1.00	4.8
44	3	2855	200	1.07	-.80	2610	3.10	4.00	35.0	2.5	20.2	30.0	1.10	15.8
9	7	2828	4700	1.30	-.80	2745	4.30	3.50	36.0	3.0	21.6	30.0	0.50	15.3

(1) G.W. - Test gross weight of the helicopter
(2) H_D - Density altitude of test
(3) t_1 - Time delay after throttle cut before response application of collective pitch
(4) A_1 - Maximum negative change of acceleration encountered during descent
(5) V_D - Maximum rate of vertical descent encounter during run
(6) t_2 - Elapsed time between throttle cut and attainment of maximum rate of descent
(7) t_3 - Elapsed time between start of "up collective" and touchdown
(8) Ω_1 - Rotor speed at start of "up collective"
(9) t_4 - Elapsed time between maximum "nose up" attitude and touchdown
(10) V_{TD} - Calibrated airspeed at touchdown
(11) Ω_2 - Rotor speed at touchdown
(12) A_2 - Change of vertical acceleration at touchdown
(13) V_{TC} - Calibrated airspeed at throttle chop

*high hover points
**yielded landing gear cross tubes

than an abrupt increase of collective pitch. There were rather consistent indications that from high hover or near high hover entry conditions, cyclic flare was possibly of greater value in reducing vertical contact velocity than the application of collective pitch, particularly when collective was not most effectively utilized. That is to say, it appeared that better landings (lower load factors - no bounce) were achieved when cyclic was utilized more fully than collective, than vice-versa. This is because the cyclic flare maintained or produced an increase in rotor speed which, with coordinated collective application, permitted more efficient utilization of the rotor energy. Touchdown then occurred with low load factors from a relatively low rotor speed of the order of 260 rpm, indicating that little rotor energy remained and the touchdown was maximum performance. It is also interesting to note that even though the low pitch blade angle was set to produce 370 rpm (the high limit red line) this value was never exceeded during cyclic flare. The drop-off in rpm following power failure more than offset the buildup of rpm in the cyclic flare.

The vertical descent velocity following power failure from high hover or near high hover is seen to increase as weight and density altitude increase. The rates of descent listed in Table I were the maximum descent rates obtained and for practical considerations can be considered to be steady state rates of descent. As forward speeds increased toward V_{cr} these rates of descent decreased accordingly. This is shown in Table II which lists runs obtained in the vicinity of h_{cr} and V_{cr}. With few exceptions, whether entry was from high hover or in the "knee" area, the incremental vertical accelerations following simulated power failure were in the order of -.75 g's.

Effects of Weight and Altitude

As previously discussed, height-velocity diagrams were individually drawn through each set of test points and then cross plots constructed of speed versus weight and altitude from which final faired H-V diagrams were drawn. This led to the cross plotting of specific controlling points on the H-V diagram such as h_{cr}, V_{cr}, h_{min} and h_{max}. These cross plots are shown in Figures 22 through 25. The high hover height, h_{min}, is shown to vary linearly with the square of the critical speed independent of weight and altitude in Figure 26.

Thus, a set of height-velocity diagrams resulting from these tests was developed for a series of weights and/or altitudes and are defined by the family of curves as shown in Figures 15 through 21. This family

TABLE II

SUMMARY OF TYPICAL DATA-AREA OF CRITICAL SPEED (V_{cr}) AND CRITICAL HEIGHT (h_{cr})

FLIGHT NO.	RUN NO.	G.W.(1) pounds	H_D(2) feet	t_1(3) sec.	A_1(4) Δ_g	V_D(5) ft/min	t_2(6) sec.	t_3(7) sec.	Ω_1(8) rad.	t_4(9) sec.	V_{TC}(10) mph	V_{TD}(11) mph	Ω_2(12) rad.	A_2(13) Δ_g
43	5	2424	-500	.30	-.6	1975	1.7	4.7	33	3.2	21.8	16.8	24	.35
38	4	2403	-100	.28	-.7	1455	1.9	3.7	34	2.0	19.4	12.8	27	.80
5	3	2422	4480	.65	-1.0	1405	2.9	4.8	34	3.8	28.4	21.0	25	.60
10	5	2398	4500	.29	-.7	1835	2.7	3.0	34	2.0	21.7	15.0	30	.60
33	11	2403	7300	.22	-.5	1826	1.8	4.8	34	3.8	26.7	24.7	27	.30
16	6	2432	9100	.30	-.7	1335	1.5	5.1	35	3.8	33.8	26.7	25	.50
19	1	2434	9420	1.0	-.8	1880	2.8	3.5	33	1.6	32.4	22.7	29	1.0
15	4	2407	9480	1.28	-.85	1920	3.0	5.1	33	3.5	35.6	21.6	26	1.0
47	6	2641	230	.87	-.6	2000	3.0	5.2	33	3.8	22.6	25.2	26	.55
47	8	2662	370	.86	-.8	2060	2.1	5.0	33	3.4	21.8	21.8	26	.80
28	16	2648	4610	.17	-.55	1960	2.2	5.5	34	4.0	28.1	22.7	25	1.1
6	7	2642	5850	.33	-.7	1735	2.6	2.1	33	1.6	31.2	28.6	30	1.75
29	13	2645	7700	.97	-.7	1940	2.5	4.0	33	3.0	34.7	28.4	26	.30
21	5	2648	9200	.30	-.6	1705	2.1	5.8	34	3.2	34.8	21.8	26	1.0
41	5	2861	340	.29	-.6	1415	1.8	4.1	34.5	3.3	27.8	21.4	26	.50
41	6	2858	420	.28	-.6	1755	2.0	5.5	34	3.7	26.6	22.9	24	.70
26	4	2857	3580	.25	-.55	1905	2.0	4.0	34	3.3	34.4	28.6	28	.20
26	5	2851	3580	.27	-.7	2000	1.7	4.8	34	3.8	34.0	31.4	25	1.0
25	4	2832	4820	.20	-.5	1470	1.8	3.3	34	2.1	36.3	32.5	29	.20
7	8	2858	5180	.29	-.7	1800	2.8	4.7	34	4.0	36.5	28.2	25	1.15

(1) G.W. - Test gross weight of the helicopter
(2) H_D - Density altitude at test
(3) t_1 - Time delay after throttle chop before responsive application of collective pitch
(4) A_1 - Maximum negative change of acceleration encountered during run
(5) V_D - Maximum rate of vertical descent encountered during run
(6) t_2 - Elapsed time between the throttle cut and attainment of maximum rate of descent
(7) t_3 - Elapsed time between "Up Collective" and touchdown
(8) Ω_1 - Rotor speed at start of "Up Collective"
(9) t_4 - Elapsed time between maximum "nose up" attitude and touchdown
(10) V_{TC} - Calibrated airspeed at throttle chop
(11) V_{TD} - Calibrated airspeed at touchdown
(12) Ω_2 - Rotor speed at touchdown
(13) A_2 - Change of vertical acceleration at touchdown

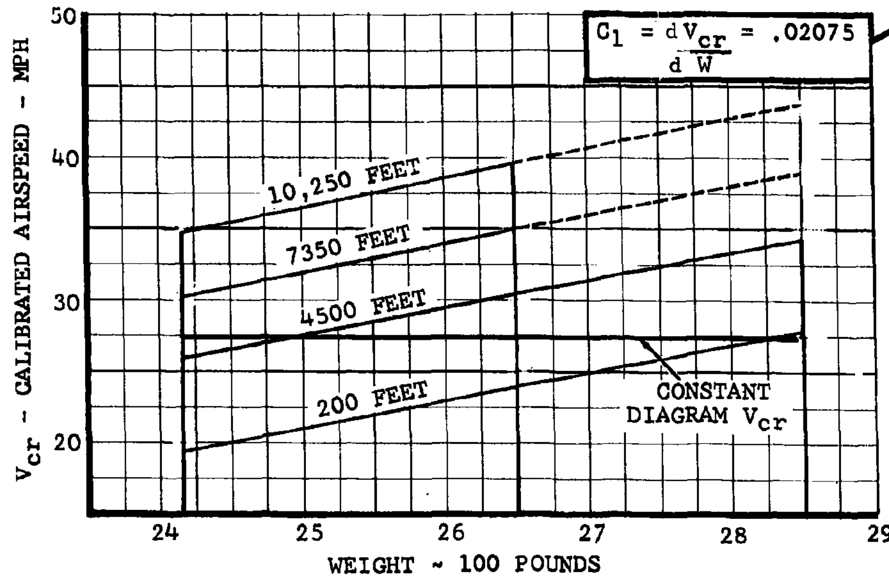

FIG. 22 CRITICAL VELOCITY (V_{cr}) VERSUS AIRCRAFT GROSS WEIGHT FOR THE RANGE OF TEST ALTITUDES

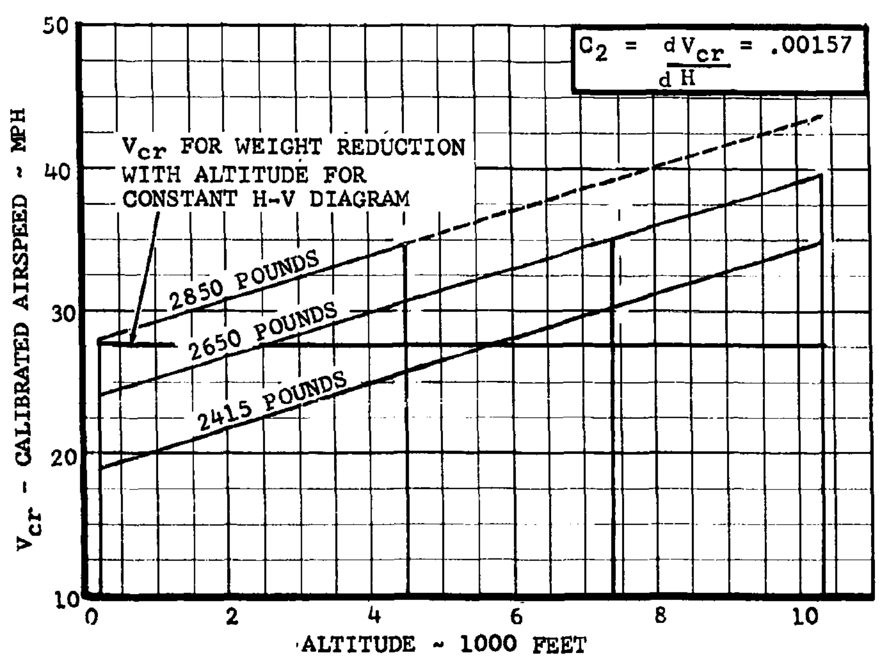

FIG. 23 CRITICAL VELOCITY (V_{cr}) VERSUS TEST ALTITUDE FOR THE RANGE OF TEST WEIGHTS

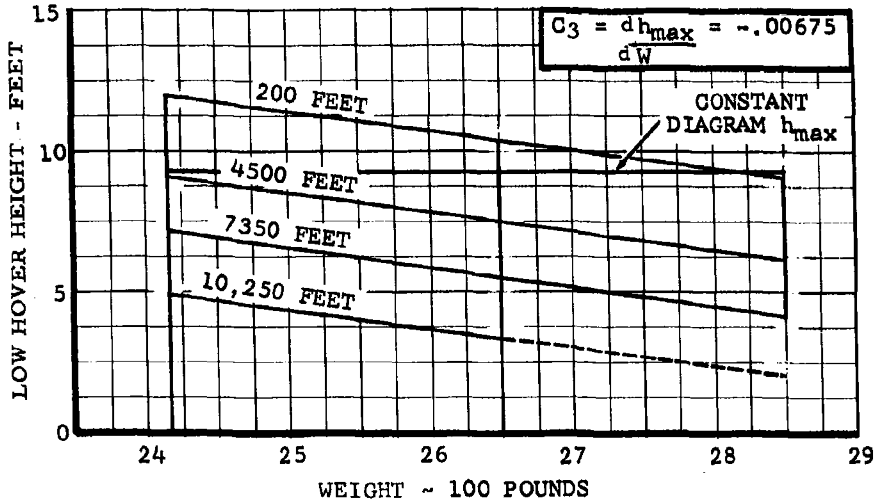

FIG. 24 LOW HOVER HEIGHT (h_{max}) VERSUS AIRCRAFT GROSS WEIGHT FOR THE RANGE OF TEST ALTITUDES

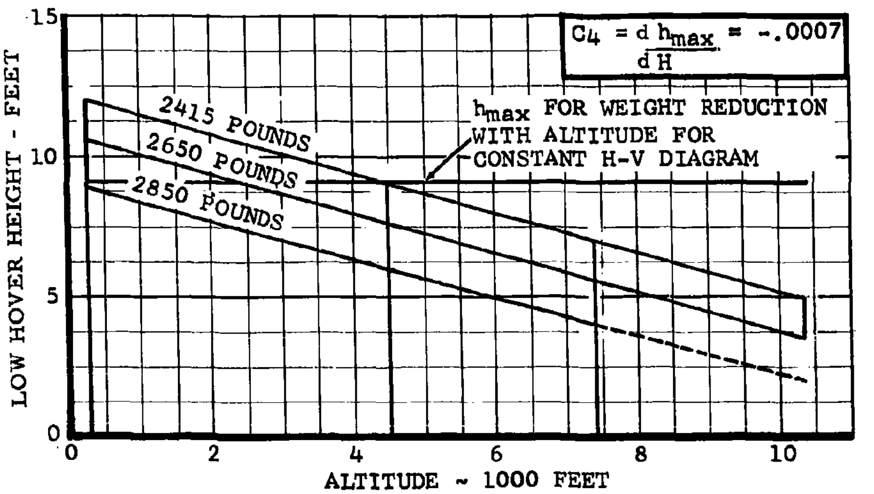

FIG. 25 LOW HOVER HEIGHT (h_{max}) VERSUS TEST ALTITUDE FOR THE RANGE OF TEST WEIGHTS

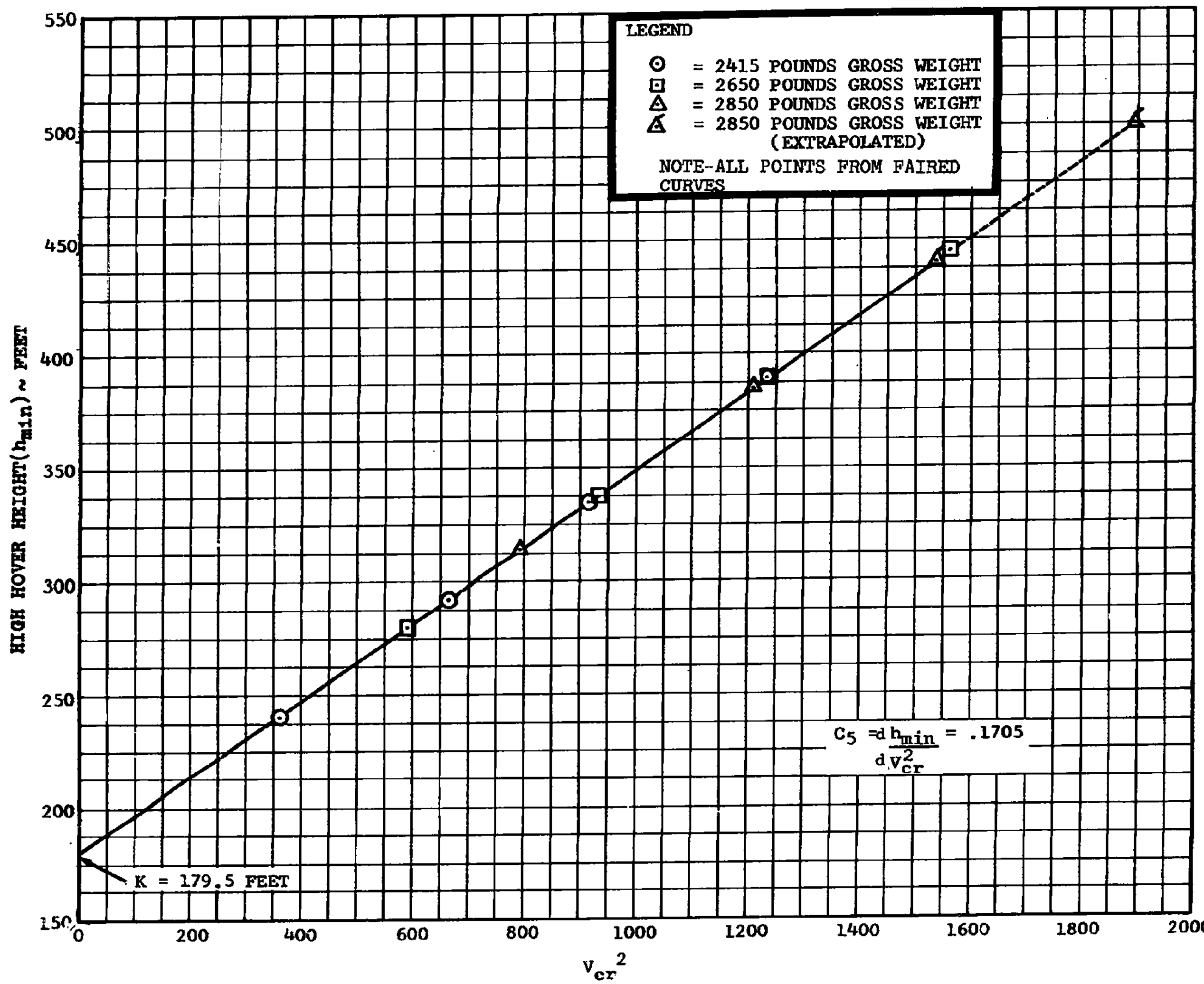

FIG. 26 HIGH HOVER HEIGHT (h_{min}) VERSUS SQUARE OF CRITICAL VELOCITY (V^2_{cr})

of curves can be defined by the following equations which are expressed in terms of the critical governing points on the H-V diagram, i.e., V_{cr}, h_{cr}, h_{max} and h_{min}. Since all of the cross plots were found to be straight lines, the equations developed are simple linear equations expressed as a function of the critical velocity, V_{cr}, or the height.

Equations

1. $V_{cr} = V_{cr\ test} + C_1 \Delta W + C_2 \Delta H$

where V_{cr} = critical velocity at a given weight and density altitude

$V_{cr\ test}$ = critical velocity obtained through test

$$C_1 = \frac{dV_{cr}}{dW}$$

$$C_2 = \frac{dV_{cr}}{dH}$$

2. $h_{max} = h_{max\ test} + C_3 \Delta W + C_4 \Delta H$

where h_{max} = low-hover height at a weight and density altitude

$h_{max\ test}$ = low-hover height obtained through testing

$$C_3 = \frac{dh_{max}}{dW}$$

$$C_4 = \frac{dh_{max}}{dH}$$

3. $h_{min} = K + C_5 V^2_{cr}$

where K = a constant (the "h_{min}" intercept)

$$C_5 = \frac{dh_{min}}{dV^2_{cr}}$$

The expression for V_{cr} also holds true for speeds at heights above and below the height for V_{cr} for approximately 50 feet, which facilitates construction of H-V diagrams at other weights and altitudes. Given

such a set of empirical equations, it would be possible to develop a family of H-V diagrams from one set of test data at any normal operating weight and altitude. The specific constants of these equations, as determined by these tests, are applicable only to the test helicopter, and unfortunately there is no other known data available with which to verify that helicopters having different basic parameters would fall within the results herein obtained. It is conceivable, however, that these relationships may hold true and only the basic size and/or shape of the H-V diagram may be affected by different helicopter parameters, such as disc loading, solidity and rotor inertia.

Throughout the range of altitudes and weights tested, there was no variation in the height, h_{cr}. For the test vehicle this height remained constant at approximately 95 feet. This fact further facilitates the construction of a family of H-V diagrams from the equations shown from a single set of test data.

Effects of Entry Trim Conditions on H-V Diagram

In the foregoing discussion of the effects of weight and altitude on the height-velocity diagram, it should be noted that H-V diagrams developed for most helicopters, and in particular all certificated helicopters, represent varying degrees of conservatism to account for so-called "average pilot capabilities." In addition, the lower portion of the diagram (low speed - low height boundary) is developed from accelerated climb out entry conditions as shown in Figure 27. The results and conclusions contained herein are based on level steady flight entry conditions and the maximum performance capabilities of the helicopter-pilot combination with the attempt made to eliminate conservatism by utilizing repeatable but superior pilot technique. The H-V diagrams developed in these tests from steady state level flight entry conditions exhibit a smooth return from h_{cr}, V_{cr}, to lower hover height, whereas the

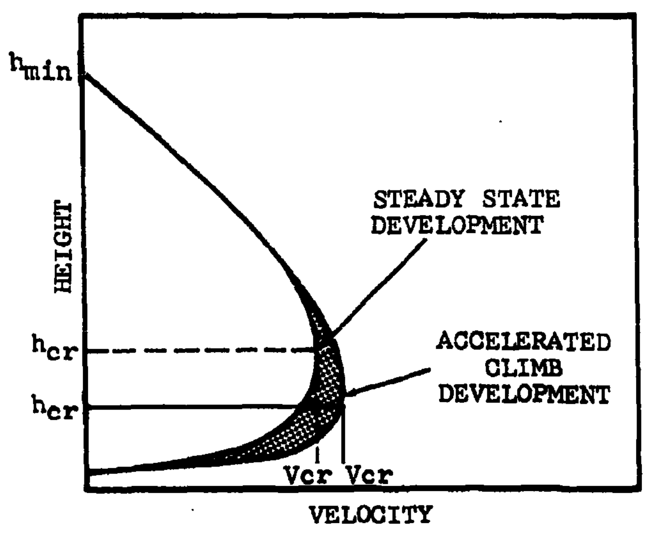

FIG. 27 Accelerated climb influence on the height-velocity diagram

general run of H-V diagrams previously developed exhibit a rather sharp curve below h_{cr} with V_{cr} occurring at a higher ratio of h_{min}/h_{cr} as shown in Figure 27. This undoubtedly is the result of a combination of accelerated climb out data in the lower boundary of the low speed regime with steady level flight data in the upper and "knee" area boundary regions. It is reasonable to expect that the cross-hatched portion shown in Figure 27 would bear the same growth factor with altitude and weight that the basic diagrams of this report exhibit.

Constant H-V Diagram for Reduction of Weight with Altitude

One approach to the problem of establishing an appropriate H-V diagram for variations of weight and altitude is to establish a diagram for maximum gross weight at sea level and hold this diagram constant while reducing weight to compensate for altitude. Such an approach is discussed in the following paragraph.

For example, Figure 23 shows that, in order to maintain one parameter-V_{cr}-constant as density altitude increases from sea level, the weight must be reduced to 2650 pounds at 2500 feet and 2415 pounds at about 5600 feet. If 2415 is the minimum weight at which the helicopter can be flown, then the diagram cannot be held to the sea level size above 5600 feet.

Since h_{min} is a function of V_{cr}, independent of weight and altitude, the upper part of the diagram is readily obtained. The lower part of the diagram does not quite follow the same pattern since the maximum altitude for a constant h_{max} is only 4500 feet. However, since the difference of height in h_{max} between 4500 feet and 5600 feet density altitudes is less than a foot, the approach is considered practical. A sample H-V diagram based upon such an approach and demonstrating how it may be handled is shown in Figure 28.

High Inertia Rotor Tests

At the conclusion of the basic test program to determine the effects of altitude, the aricraft was returned to Fort Worth, Texas, to test for the effects of increased rotor inertia on the H-V diagram. Ten pound weights were installed in the tips of the rotor blades. This additional weight increased the rotor moment of inertia by 25 percent. Tests were then

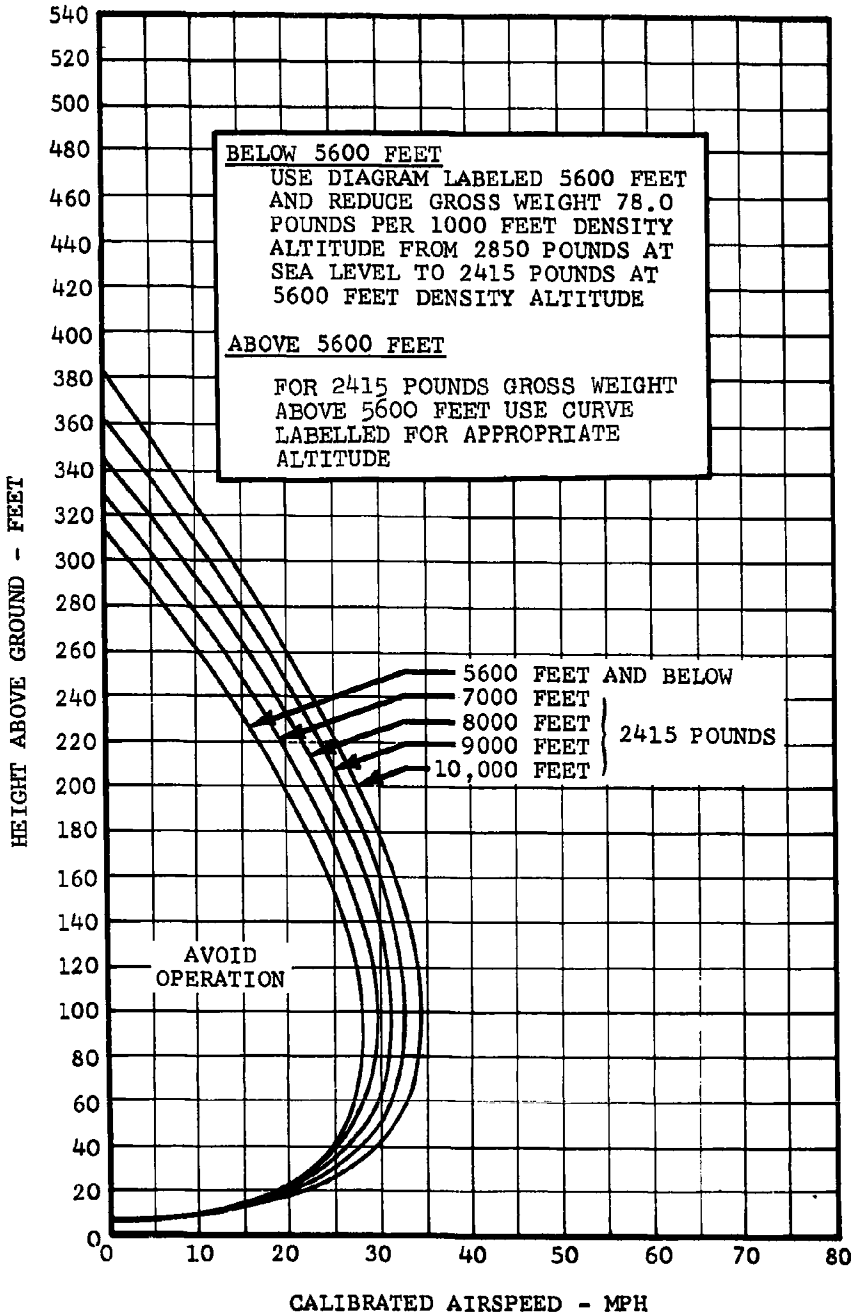

FIG. 28 HEIGHT-VELOCITY DIAGRAM
CONSTANT DIAGRAM - WEIGHT REDUCTION

conducted principally at a gross weight of 2850 pounds at seal level to determine the effect of increased rotor inertia on the H-V diagram. The time allotted to this program was limited, and when one of the landings resulted in a yielded landing gear cross tube, the program was discontinued. Sufficient data was obtained, however, to develop one H-V diagram which is shown in Figure 29. This is similar to the final curve of Figure 12 which is the standard rotor H-V diagram. The higher inertia rotor blade test data fits the curve of Figure 12 readily, and there appears to be little difference between the standard rotor and the high inertia rotor for the complete H-V diagram shown.

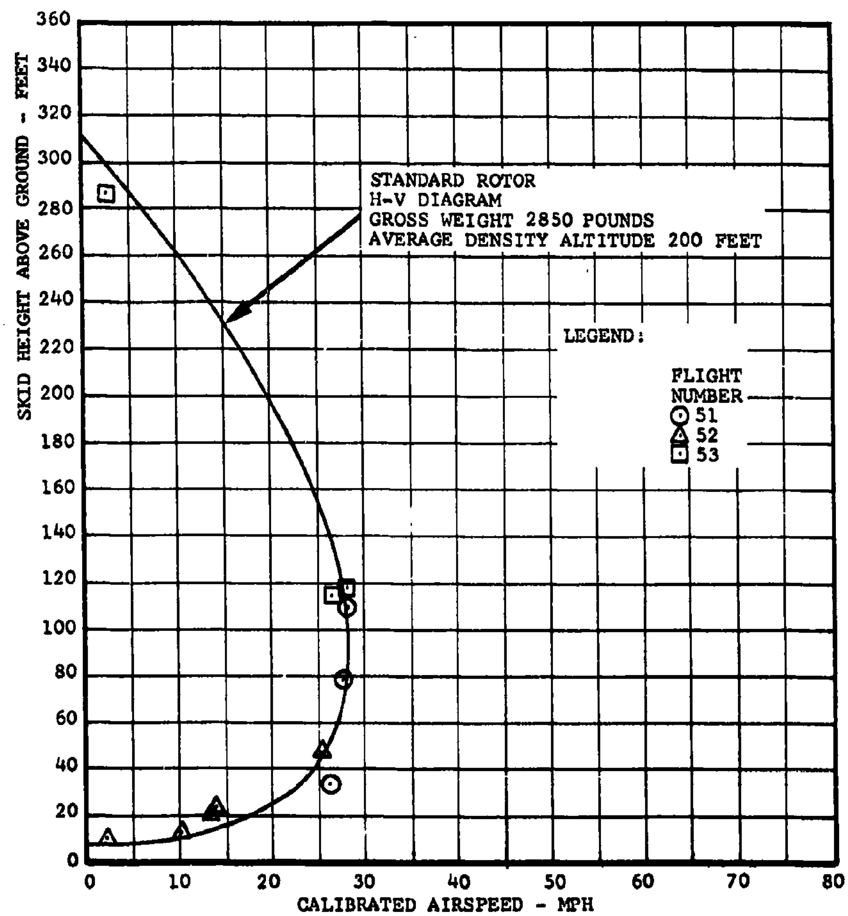

FIG. 29 RELATIONSHIP OF HIGH ROTOR INERTIA H-V POINTS TO STANDARD ROTOR H-V DIAGRAM

CONCLUSIONS

Based upon the tests of a light weight, single engine, single rotor helicopter and an analysis of the test results, it is concluded that:

1. The height-velocity diagrams for this helicopter at different weights and altitudes evolve into a family of curves for the altitudes and weights tested.

2. This family of curves is defined by equations involving key points on the H-V diagram such as V_{cr}, h_{cr}, h_{min}, and h_{max}. From test data obtained at any one gross weight and altitude and the resulting H-V diagram, it is therefore possible to construct H-V diagrams for other weights and altitudes using the following relationships, provided the appropriate constants are known:

   a. V_{cr} is a linear function of weight or altitude.

   b. h_{max} is a linear function of weight or altitude.

   c. h_{min} is a linear function of $V^2{}_{cr}$.

   d. The height (h_{cr}) for critical velocity (V_{cr}) is essentially constant and is independent of variations in weight and density altitude.

3. The best landings (lowest load factor) were made when coordinated application of both cyclic and collective pitch were effected sufficiently before touchdown to utilize full rotor energy.

ACKNOWLEDGEMENTS

The Program Manager, Mr. Theodore W. Sanford, Jr., of the Flight Section, Engineering and Safety Division, Aircraft Development Service, Federal Aviation Agency, Washington, D. C., planned, established, and directed a research sub-program on helicopter auto-rotation performance Number 343-010. The first project Number 343-010-01V of this sub-program is a flight test task to determine how density altitude effects the auto-rotation landing performance of a light single engine helicopter. The Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey, accepted the task of management and direction of this initial project.

This report, FAA Technical Report ADS-1, presents the results of the initial project as prepared by the Project Manager, Mr. William J. Hanley and his consultant, Mr. Gilbert DeVore of the Systems Research and Development Service.

Appreciation is expressed for the cooperation of the Bell Helicopter Company whose support made the execution of this project possible. The success of the program was notable enhanced by the efforts of the test pilot, Mr. Irwin Franklin, who had the courage and enthusiasm to prosecute the piloting assignment. The exceptional skills, efforts, and interest of the Bell Helicopter Company flight test crew also represented a valuable contribution in the accomplishment of the overall mission.

Appreciation is expressed to the NASA, VTOL Branch of the Aerospace Mechanics Division, Langley Research Center, for their technical assistance.

Appreciation is expressed to the Helicopter Section, Flight Test Division of the U. S. Navy Air Test Center, Patuxent River, Maryland, for their technical assistance.

Within SRDS, the required support of the test program was extensive, and the effective and enthusiastic support of the Technical Services Division and the Supporting Services Division was vital in the successful completion of the project.

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1. Alexander Klemin, Principles of Rotary Wing Aircraft, Reprint Aero Digest, 1945.

2. A. Gessow and G. C. Meyers, Aerodynamics of the Helicopter, The MacMillan Co., C 1952

3. D. Dommasch, Elements of Propeller and Helicopter Aerodynamics, Pitman Pub. Co., C 1953.

APPENDIX I

TEST AIRCRAFT SPECIFICATIONS

Significant specifications of the test aircraft and its powerplant are as follows:

1. Powerplant: Lycoming Model TVO-435

   a. Horsepower rating - 220BHP @ 3200 rpm, max. continuous

      - 260BHP @ 3200 rpm, 2 min. limit

2. Weight, gross:

   a. Maximum certified - 2850 pounds

3. Service ceiling:

   a. @ 2850 pounds - 18,500 feet

4. Hovering ceiling:

   a. @ 2850 pounds - 18,000 feet - in ground effect

   b. @ 2850 pounds - 15,000 feet - out of ground effect

5. Maximum speed @ 2850 pounds:

   a. Sea level to 10,000 feet - 105 mph

6. General data:

   a. Rotor Diameter - 37 feet, 1.5 inches

   b. Rotor disc area - 1083.00 square feet

   c. Chord - 11.00 inches

   d. Airfoil Section - NACA .0015

e. Solidity ratio - .0314

f. Disc loading @ 2850 pounds - 2.631 pounds/feet^2

TEST INSTRUMENTATION

A brief description of the test instrumentation utilized for this flight test program is as follows:

1. Airborne

The airborne quantitative information measured was:

a. Airspeed

b. Altitude

c. Rotor rpm

d. Engine rpm

e. Collective Stick Position

f. Cyclic Stick Position

g. Acceleration (all axes)

h. Fuselage Attitude

i. Angular Velocity (all axes)

j. Manifold Pressure

k. Vertical Velocity

l. Fuel total

m. Landing Gear Stresses

This information was recorded on an oscillograph, photopanel and/or both as considered appropriate. Figure I shows the installation of the recording equipment and some of the basic instrumentation

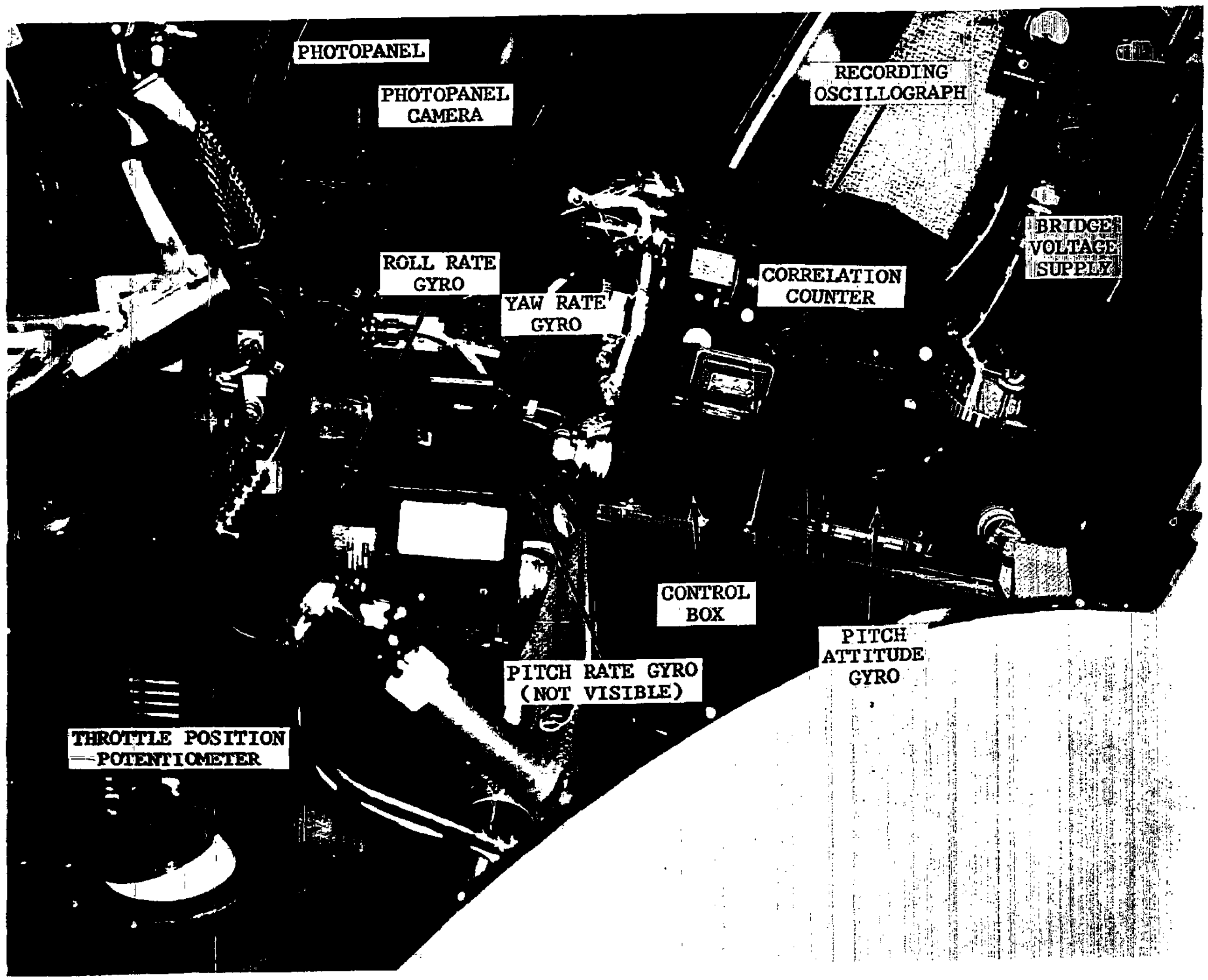


FIG. 1 AIRBORNE INSTRUMENTATION

within the cabin of the aircraft. Figures 2a and 2b point out the location of some of the airframe instrumentation and exterior accessories utilized for the control and accomplishment of the test.

2. Ground

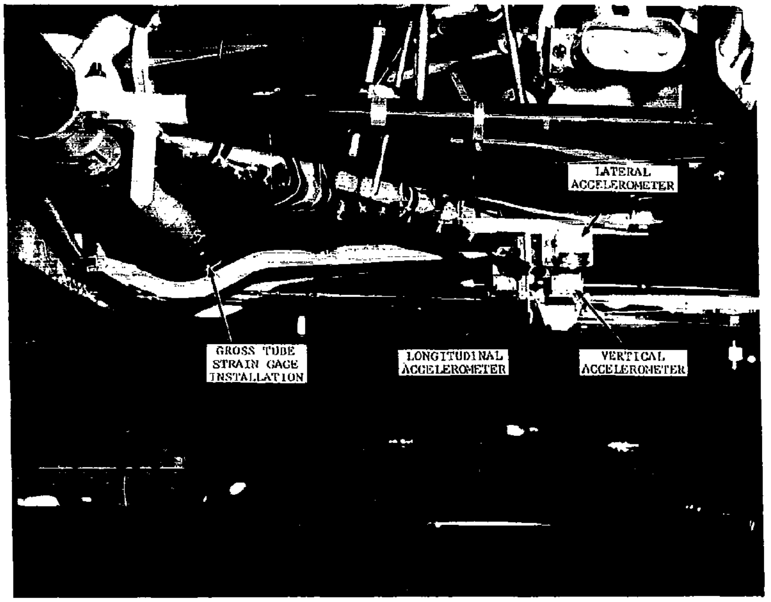
Space position equipment utilized for tracking the aircraft is shown in Figures 3a and 3b. Two photographic flight path analyzers were utilized so as to augment each other's photographic capability. The motion picture type of flight analyzer, because of its limited field of view, was used specifically for the low height-over-the-ground tests that involved primarily vertical movement of the helicopter. The still picture type flight path analyzer was used primarily for flights that involved high heights-over-the-ground and relatively large horizontal helicopter movements. A sample photographic plate is shown in Figure 4.

Meteorological equipment utilized for recording atmospheric conditions during the flight tests is shown in Figures 5a and 5b.

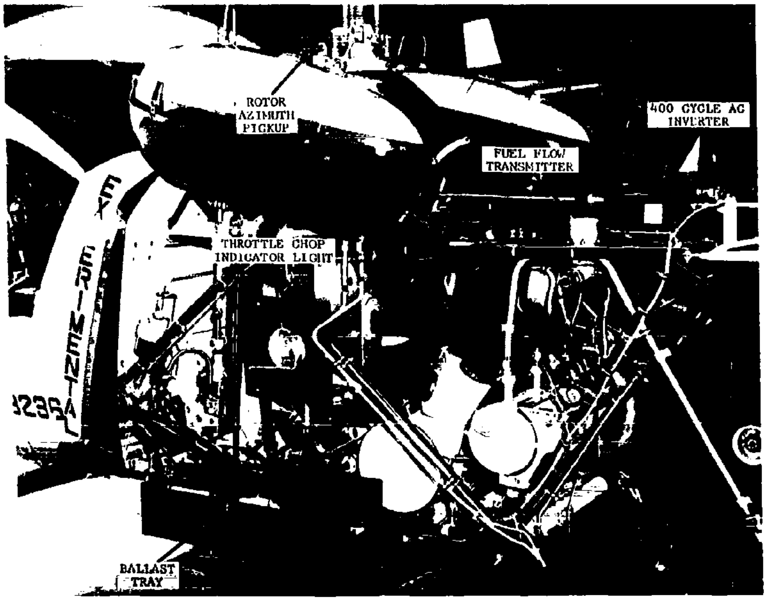
The wind speed and direction recorder was a battery-operated portable field instrument capable of recording wind speed from 3/4 mph to 6 mph and wind directions throughout 354 degree azimuth. The equipment's low threshold and high sensitivity permitted spontaneous and accurate measurement of small scale fluctuations in wind direction and velocity.

For measuring atmospheric pressure a portable, precision aneroid barometer with an indicating range capability of 1030 to 540 millibars was utilized. The versatility and high accuracy of the instrument made it ideal for use at all of the selected test sites.

Wet and dry bulb air temperatures were measured with a portable electrically aspirated psychrometer. These measurements together with accurate pressure indications were the basis for accurate determination of the density altitude at the time of testing.

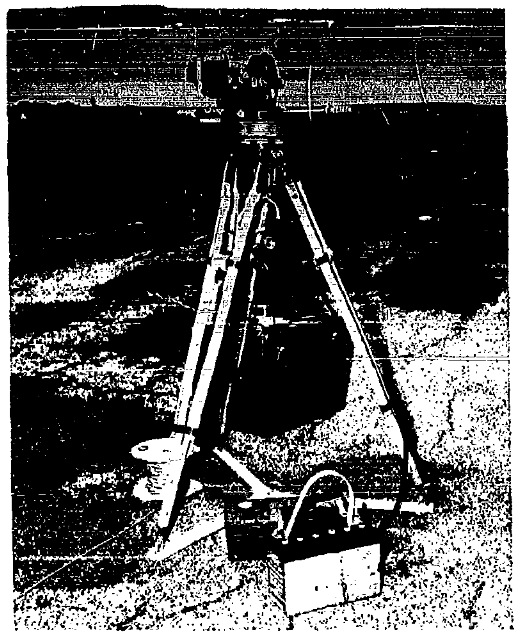


A. ACCELEROMETERS AND STRAIN GAGES

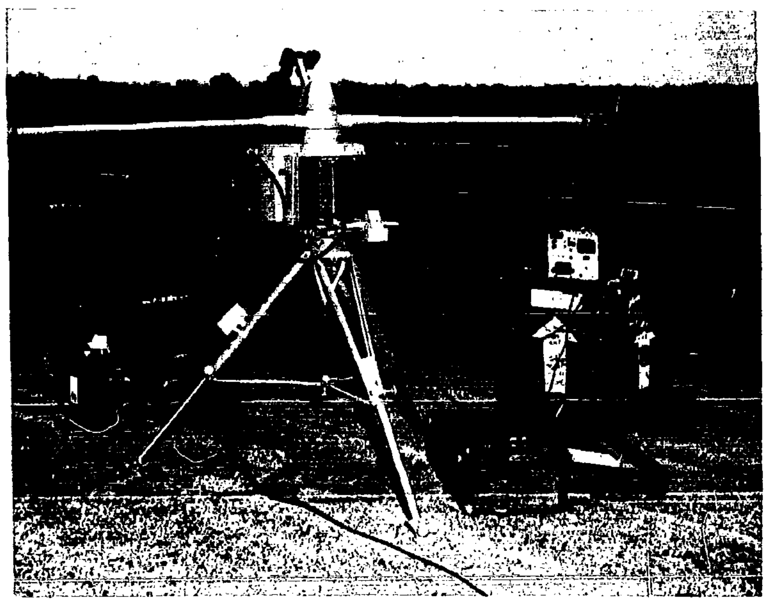


B. SPECIAL EXTERIOR ACCESSORIES

FIG. 2 AIRFRAME INSTRUMENTATION AND SPECIAL ACCESSORIES



A. PHOTOGRAPHIC FLIGHT PATH ANALYZER
(MOTION PICTURE)



B. PHOTOGRAPHIC FLIGHT PATH ANALYZER
(STILL PICTURE)

FIG. 3 SPACE POSITIONING EQUIPMENT

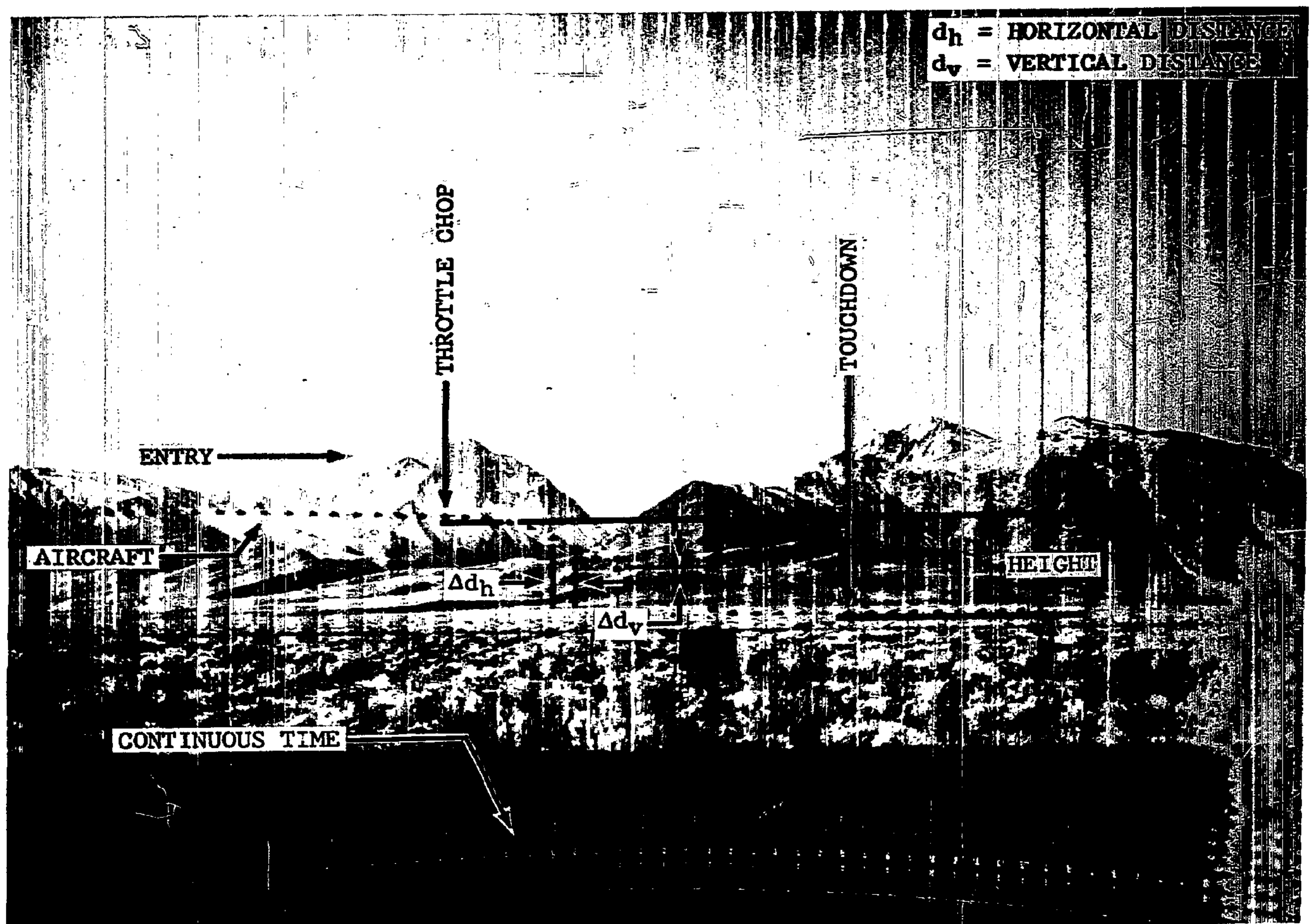
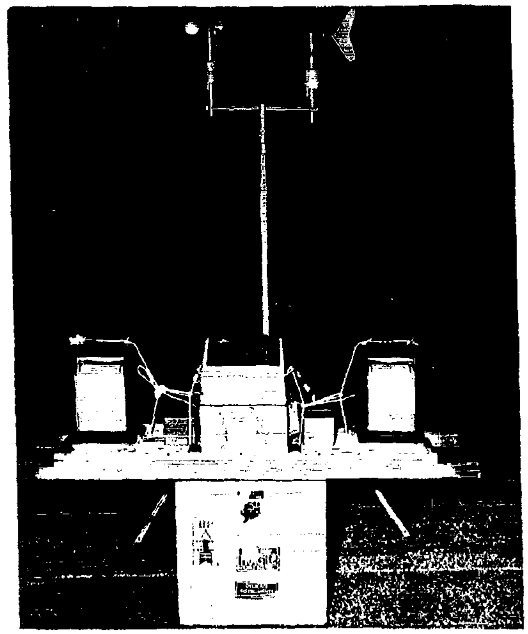
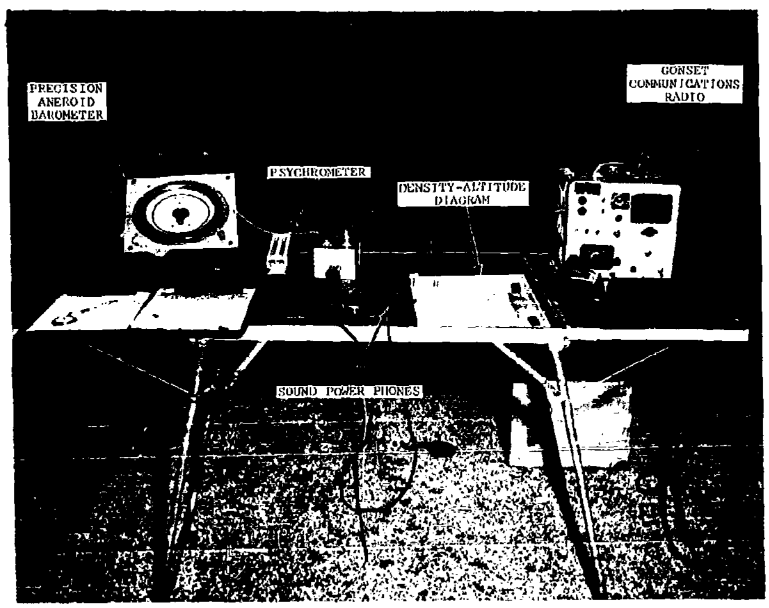


FIG. 4 TYPICAL FLIGHT PATH PHOTOGRAPH AND REDUCTION TECHNIQUE



A. WIND SPEED AND DIRECTION RECORDER



B. TEMPERATURE AND PRESSURE INSTRUMENTS
HUMIDITY AND AIR DENSITY CHARTS

FIG. 5 METEOROLOGICAL EQUIPMENT

APPENDIX II

PILOT'S COMMENTS

A resumé of the test pilot's subjective comments on procedures and techniques is as follows:

"Some method had to be devised to ascertain whether a test was good, conservative, or otherwise. This method, whatever it might be, naturally should be and was used at all sites during all landings. After discussion on this specific subject, it was decided that there was one and only one method that would satisfy the requirements of this investigation.

"Since there are no known parameters available which can be used to determine a degree of conservatism, it became obvious that none of the final test points to be plotted should be conservative. In view of this, it was necessary to extract the maximum capability of the helicopter during each and every test point during the entire operation. Necessarily, pilot opinion had to be relied upon in the final determination of the validity of a landing of test point. In view of this, it became obvious that some of the landings could become hazardous. Regardless of this, a conscientious and sincere effort was made to validate all final landings for test points. This was accomplished by repeating specific landings. Some final points were substantiated, unfortunately, by yielding the cross tube of the landing gear.

"While on the subject of the actual landings, it may be timely to discuss technique used in the execution of the landings. Since there are several methods or techniques which can be employed to accomplish a normal autorotation landing, one method had to be employed throughout this program. The method used could hardly be classified as a specific technique as such. It became obvious a short time after the program commenced at Bishop Airport that each entry condition at each gross weight at each point on the curve presented an entirely different problem with respect to the method of recovery. Therefore, the methods were such that the landings were effected by utilizing the basic parameters available as their degree of effectiveness dictated.

"These parameters are rotor rpm, observed airspeed, available collective pitch and rate of descent. For example, at low height and low speed entry condition where the collective cannot be lowered fully without penalty of high rate of descent, the landing is affected by utilizing airspeed and collective pitch available. In this case, these parameters are not at optimum, but the low sink rate makes a safe landing possible. On the other hand, at higher heights, higher rates of descent result because of the time involved from entry to touchdown. With the greater time lapse, were the collective not lowered, rotor rpm decay would become prohibitive. Therefore, in this case, optimum airspeed and rotor rpm must be attained to accomplish the task of arresting the rate of descent at touchdown. From this same entry condition, the approach to the landing can be varied somewhat in that one second after the throttle is closed, the collective pitch can be lowered immediately and quickly. This, in effect, accelerates the rate of descent with the final rate of descent at recovery unnecessarily high even though the higher observed airspeed is obtained; therefore rendering the landing even more critical in that the pilot's reaction to this condition must be precise in all respects.

"The method employed during the test was to lower the collective at a slower rate. This prevented a high acceleration of descent rate, and the rate of recovery was such that it appeared easier to cope with as the effective ground speed was greater due to the difference in glide slope from that of the former method.

"Inasmuch as each landing had to be critical to be a valid test point, it can be seen that the recovery method used was dictated by the entry condition. Maximum usage of the parameters affecting each landing was utilized in obtaining what is believed to be the optimum in the performance of the helicopter during the entire test program."

APPENDIX III

TYPICAL TIME HISTORY PLOTS

HEIGHT - VELOCITY TEST

FLIGHT NO. 49 RUN NO. 2 COUNTER NO. 968

GROSS WEIGHT 2649 LBS. DENSITY ALTITUDE -140 FEET

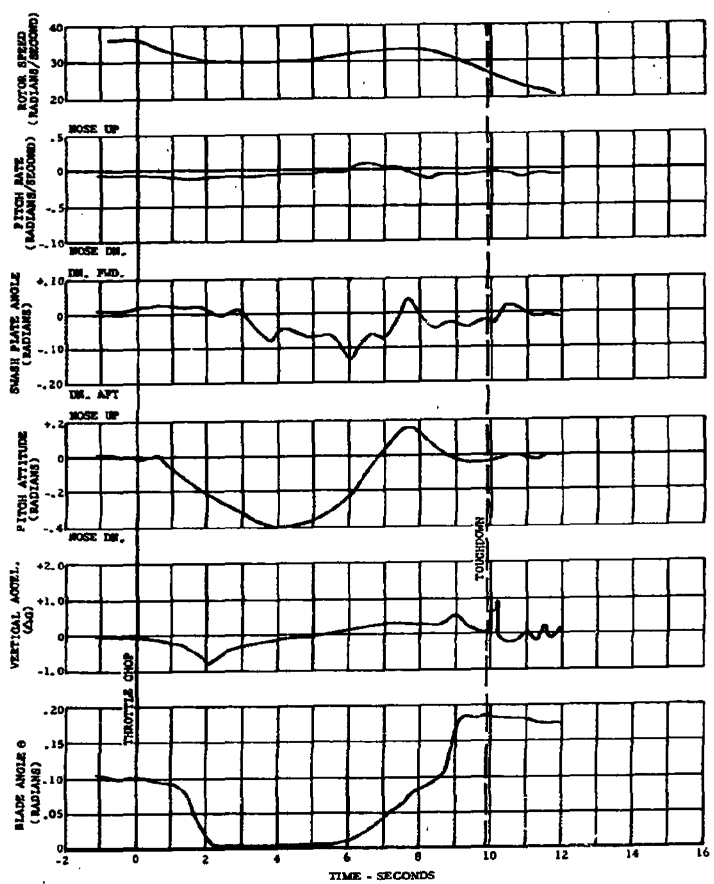
WIND COMPONENT VELOCITY +1.6 MPH

SKID HEIGHT 258 FEET } AT THROTTLE CHOP

CALIBRATED AIRSPEED 1.6 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED 18.8 MPH } AT LANDING

ACCELERATION 1.0 G's } AT LANDING



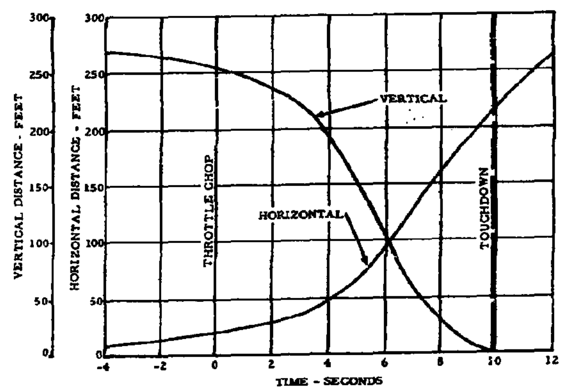


FIG. 1 TYPICAL TIME-HISTORY PLOT
HIGH HOVER AREA AT INTERMEDIATE GROSS WEIGHT

HEIGHT - VELOCITY TEST

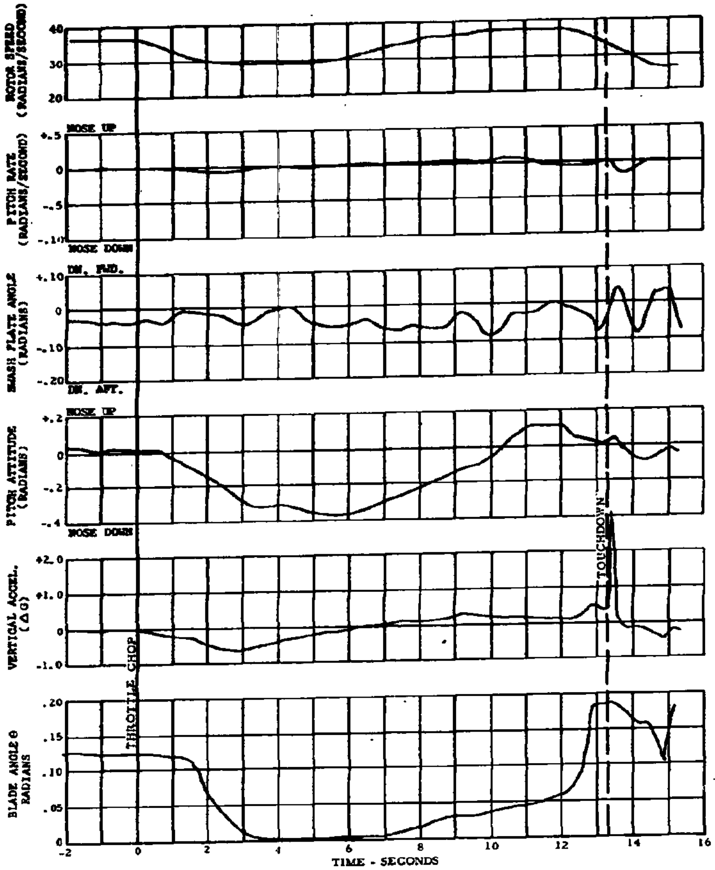
FLIGHT NO. 20 RUN NO. 15 COUNTER NO. 140

GROSS WEIGHT 2642 LBS. DENSITY ALTITUDE 11,150 FEET

WIND COMPONENT VELOCITY +0.8 MPH

SKID HEIGHT 486.0 FEET
CALIBRATED AIRSPEED 0.8 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED 21.1 MPH
ACCELERATION 3.1 G's } AT LANDING



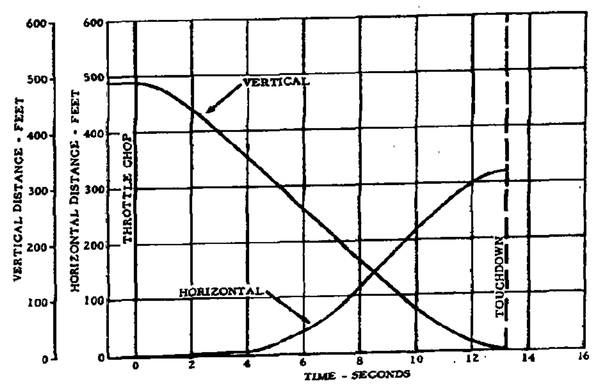
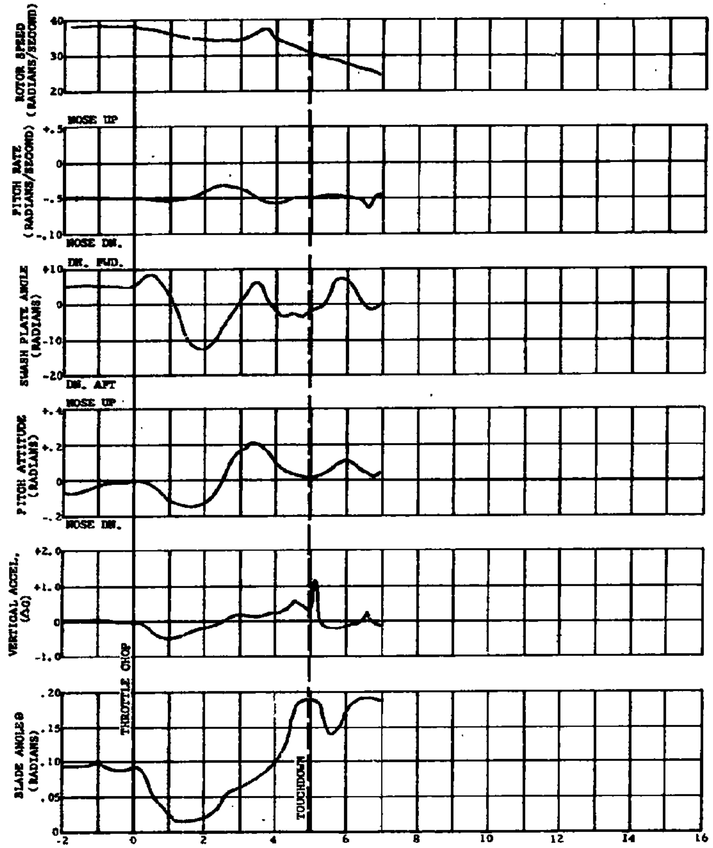


FIG. 2 TYPICAL TIME-HISTORY PLOT
HIGH HOVER AREA AT INTERMEDIATE GROSS WEIGHT



HEIGHT - VELOCITY TEST

FLIGHT NO. 47 RUN NO. 4 COUNTER NO. 928

GROSS WEIGHT 2647 LBS. DENSITY ALTITUDE 260 FEET

WIND COMPONENT VELOCITY -1.5 MPH

SKID HEIGHT 72 FEET
CALIBRATED AIRSPEED 20.2 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED 18.2 MPH
ACCELERATION 1.2 G's } AT LANDING

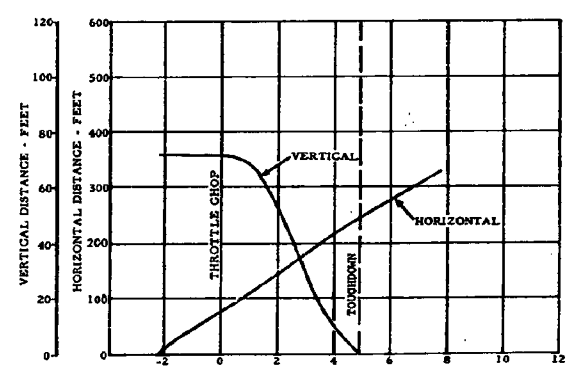


FIG. 3 TYPICAL TIME-HISTORY PLOT AREA NEAR CRITICAL VELOCITY (V_{cr}) AT INTERMEDIATE GROSS WEIGHT

HEIGHT - VELOCITY TEST

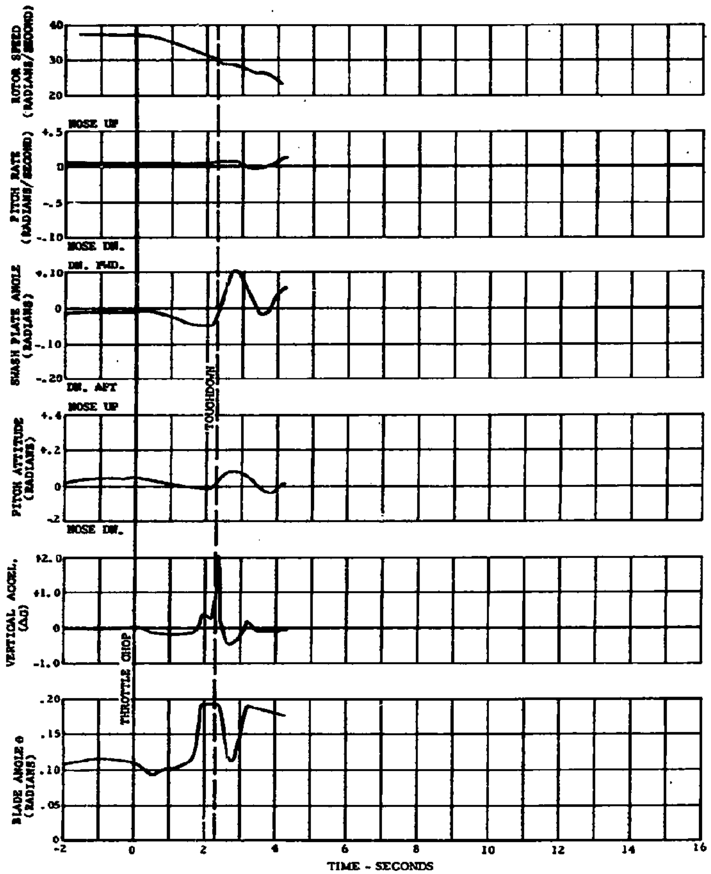
FLIGHT NO. 47 RUN NO. 16 COUNTER NO. 940

GROSS WEIGHT 2650 LBS. DENSITY ALTITUDE 610 FEET

WIND COMPONENT VELOCITY -0.3 MPH

SKID HEIGHT 8.7 FEET
CALIBRATED AIRSPEED -0.3 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED -0.3 MPH
ΔACCELERATION 2.0 G's } AT LANDING



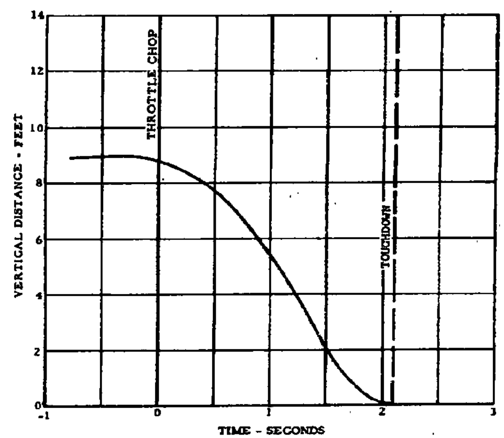


FIG. 4 TYPICAL TIME-HISTORY PLOT
LOW HOVER AREA AT INTERMEDIATE GROSS WEIGHT

HEIGHT - VELOCITY TEST

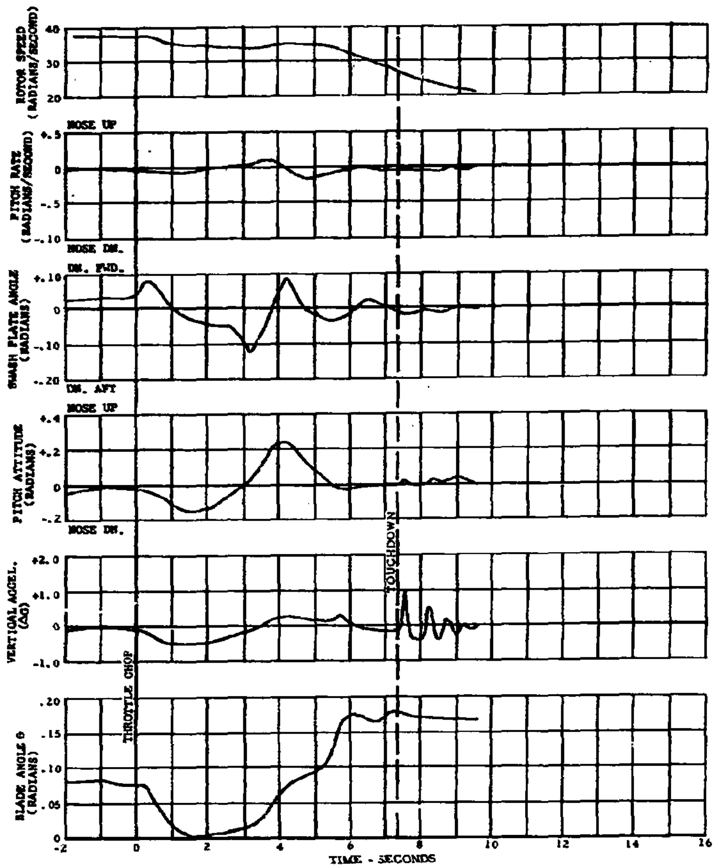
FLIGHT NO. 21 RUN NO. 5 COUNTER NO. 210

GROSS WEIGHT 2648 LBS. DENSITY ALTITUDE 9,200 FEET

WIND COMPONENT VELOCITY -1.0 MPH

SKID HEIGHT 94.0 FEET
CALIBRATED AIRSPEED 34.8 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED 21.8 MPH
Δ ACCELERATION 1.0 G's } AT LANDING



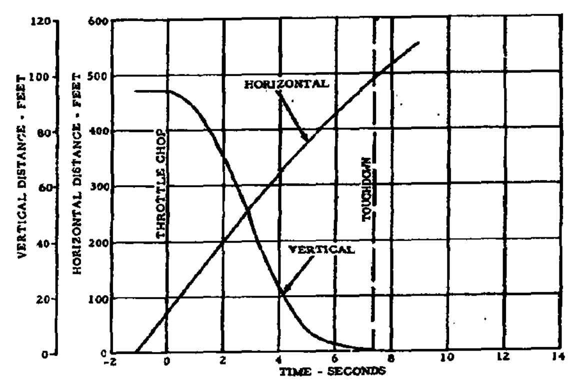
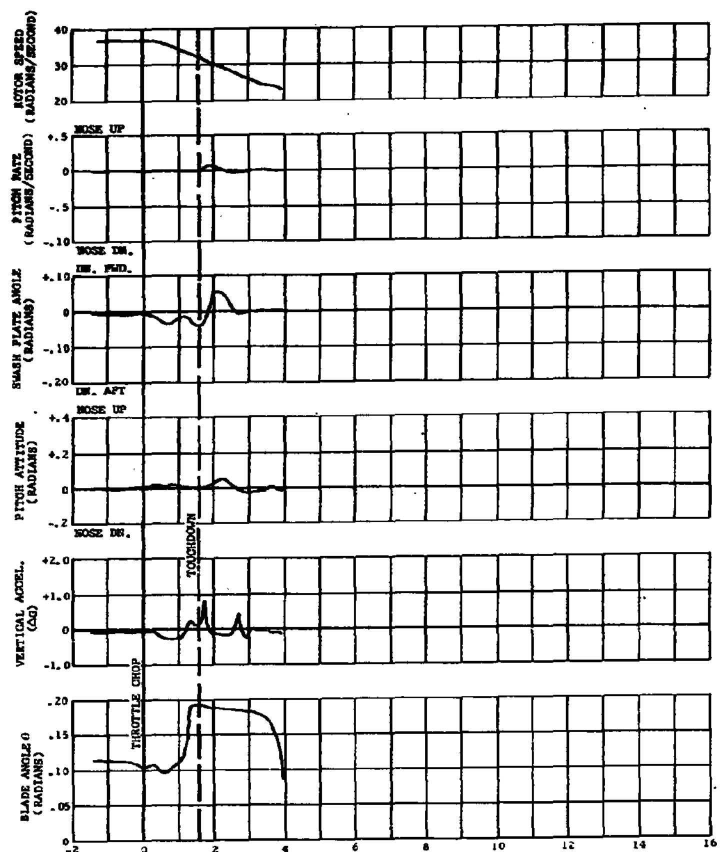


FIG. 5 TYPICAL TIME-HISTORY PLOT AREA NEAR CRITICAL VELOCITY (V_{cr}) AT INTERMEDIATE GROSS WEIGHT



HEIGHT - VELOCITY TEST

FLIGHT NO. 17 RUN NO. 1 COUNTER NO. 042

GROSS WEIGHT 2657 LBS. DENSITY ALTITUDE 10,920 FEET

WIND COMPONENT VELOCITY -1.5 MPH

SKID HEIGHT 3.0 FEET
CALIBRATED AIRSPEED -1.5 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED -1.5 MPH
ACCELERATION 0.9 G's } AT LANDING

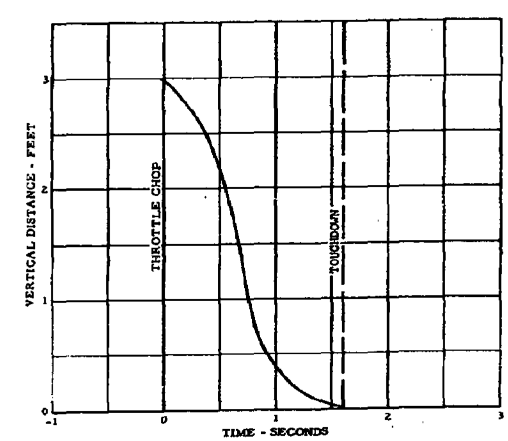
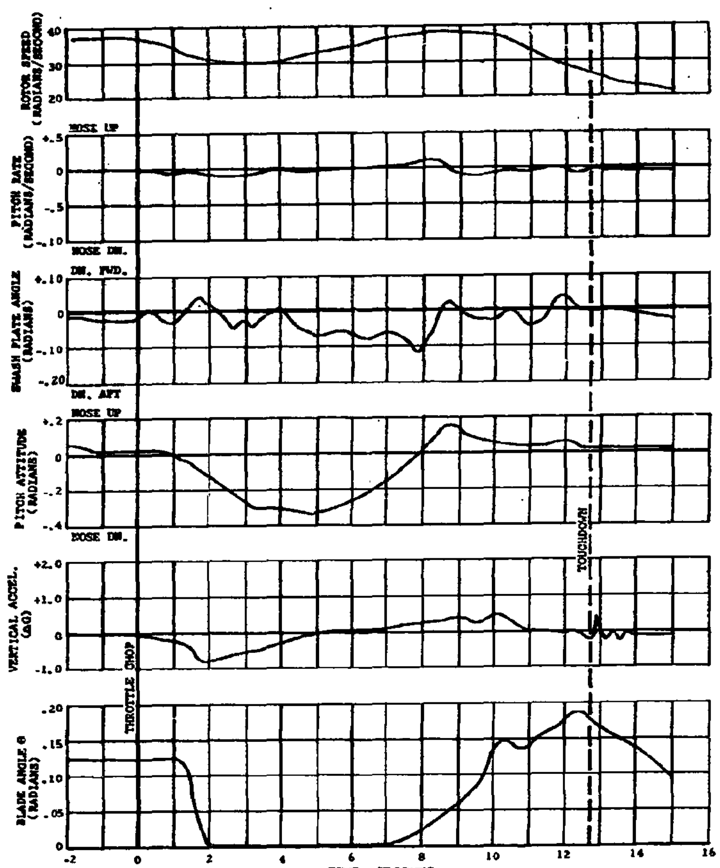


FIG. 6 TYPICAL TIME-HISTORY PLOT
LOW HOVER AREA AT INTERMEDIATE GROSS WEIGHT



HEIGHT - VELOCITY TEST

FLIGHT NO. 9 RUN NO. 5 COUNTER NO. 764

GROSS WEIGHT 2816 LBS. DENSITY ALTITUDE 4,450 FEET

WIND COMPONENT VELOCITY +2.9 MPH

SKID HEIGHT 358.5 FEET
CALIBRATED AIRSPEED 2.7 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED 20.4 MPH
Δ ACCELERATION 0.4 G's } AT LANDING

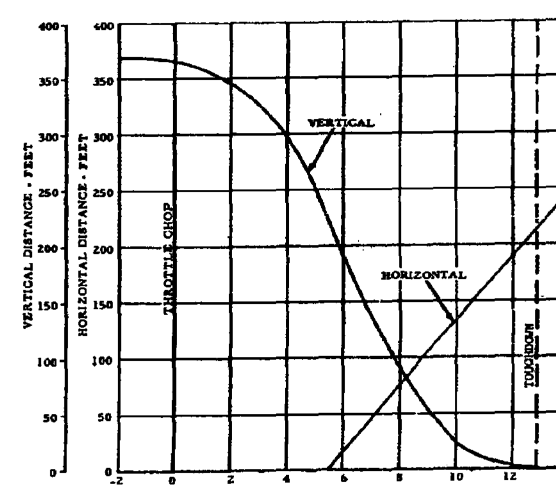


FIG. 7 TYPICAL TIME-HISTORY PLOT
HIGH HOVER AREA AT MAXIMUM GROSS WEIGHT

HEIGHT - VELOCITY TEST

FLIGHT NO. 5 RUN NO. 10 COUNTER NO. 681

GROSS WEIGHT 2424 LBS. DENSITY ALTITUDE 5130 FEET

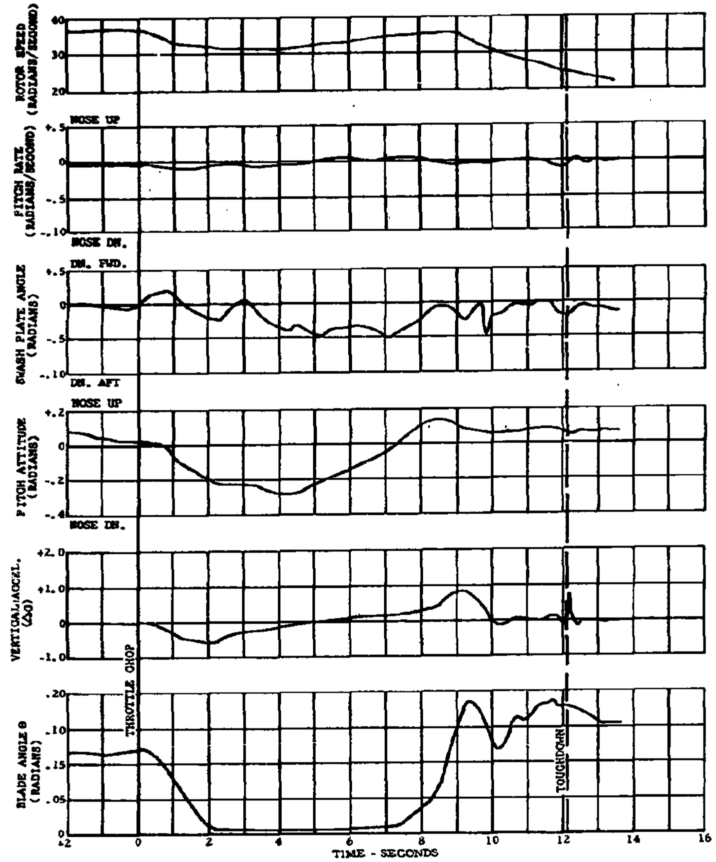
WIND COMPONENT VELOCITY 0 MPH

SKID HEIGHT 282.5 FEET } AT THROTTLE CHOP

CALIBRATED AIRSPEED 0 MPH } AT THROTTLE CHOP

CALIBRATED AIRSPEED 10.5 MPH } AT LANDING

ACCELERATION 0.7 G's } AT LANDING



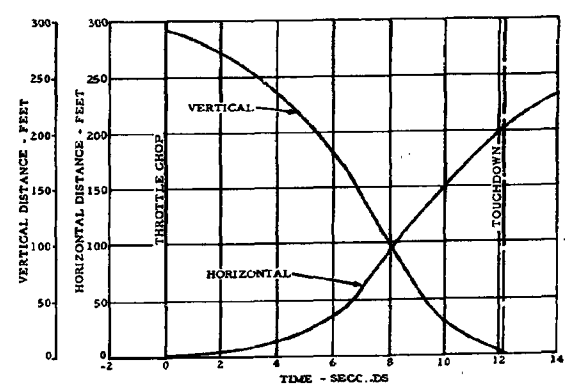


FIG. 8 TYPICAL TIME-HISTORY PLOT
HIGH HOVER AREA AT LOW GROSS WEIGHT.

APPENDIX IV

SUMMARY OF HEIGHT-VELOCITY DIAGRAM FLIGHT TEST DATA

TABLE I

SUMMARY OF HEIGHT-VELOCITY DIAGRAM FLIGHT TEST DATA

FLIGHT NO.	RUN NO.	DATE 1962	AIRCRAFT GROSS WEIGHT POUNDS	DENSITY ALTITUDE FEET	WIND COMPONENT MPH	THROTTLE CHOP HEIGHT FEET	THROTTLE CHOP V_{cal} MPH	LANDING V_{cal} MPH	LANDING Δ ACC. g's	TIME DELAY SECONDS	NOTES
3	4	9/23	2403	4500	-1.8	52.5	27.1	10.5	1.0	0.30	
3	6	9/23	2397	4520	-0.5	50.5	25.8	7.3	0.75	0.26	
3	18	9/23	2398	5270	+1.0	125.5	24.9	16.7	1.3	0.93	
4	4	9/23	2639	5890	+2.6	6.5	2.4	2.4	2.5	0.02	
4	8	9/23	2643	6220	+2.4	6.0	12.3	13.3	1.1	0.10	
4	12	9/23	2631	6275	+0.1	8.5	19.1	16.9	0.85	0.10	
5	3	9/24	2422	4480	-0.7	80.5	28.4	21.0	0.6	0.65	
5	6	9/24	2408	4810	+0.4	144.5	23.3	22.0	0.75	0.70	
5	10	9/24	2424	5130	0.0	282.5	0.0	10.5	0.7	0.63	
6	3	9/24	2656	5650	-1.3	22.5	22.1	20.0	0.6	0.27	
6	5	9/24	2652	5680	+0.7	37.5	32.1	23.7	0.9	0.32	
6	6	9/24	2646	5680	-1.9	39.5	28.6	21.6	1.7	0.29	
6	7	9/24	2642	5850	+0.5	83.5	31.2	28.6	1.75	0.33	
7	2	9/25	2862	4830	+2.2	13.5	27.9	23.6	1.1	0.30	
7	4	9/25	2873	5000	+2.6	25.5	29.6	22.3	1.3	0.28	
7	7	9/25	2861	5180	+1.0	120.5	36.3	23.8	1.0	0.20	
7	8	9/25	2858	5180	0.0	116.5	36.5	28.2	1.15	0.29	
7	12	9/25	2852	5330	+1.5	69.5	39.6	30.6	1.1	0.27	
8	4	9/27	2649	5950	+0.5	208.0	25.0	20.3	0.3	0.55	
9	5	9/27	2816	4450	+2.9	358.5	2.7	20.4	0.4	1.00	
9	7	9/27	2828	4700	+2.4	259.5	15.3	21.6	0.5	1.30	
9	8	9/27	2823	4730	+2.2	222.5	17.2	23.4	2.5	1.00	(1)
10	5	9/28	2398	4500	+2.0	109.5	21.7	15.0	0.6	0.29	

FLIGHT NO.	RUN NO.	DATE 1962	AIRCRAFT GROSS WEIGHT POUNDS	DENSITY ALTITUDE FEET	WIND COMPONENT MPH	THROTTLE CHOP HEIGHT FEET	THROTTLE CHOP V_{cal} MPH	LANDING V_{cal} MPH	LANDING ΔACC. g's	TIME DELAY SECONDS	NOTES
10	7	9/28	2419	4500	+2.3	229.5	11.7	17.5	0.2	1.32	
10	12	9/28	2409	5150	+2.4	10.0	2.2	2.2	1.4	0.10	
10	14	9/28	2404	5280	+1.3	10.5	12.9	14.1	0.9	0.10	
10	16	9/28	2400	5400	+1.1	15.5	20.3	20.3	0.55	0.25	
14	3	10/5	2422	9740	+3.0	19.5	27.2	21.2	0.5	0.10	
14	12	10/5	2411	10100	+1.2	5.75	1.2	1.2	0.2	0.10	
14	14	10/5	2426	10350	+1.3	10.0	12.0	13.0	0.7	0.35	
14	15	10/5	2420	10420	-1.5	11.5	16.3	15.2	0.4	0.23	
15	4	10/6	2407	9480	-0.5	117.0	35.6	21.6	1.0	1.28	
15	11	10/6	2407	10330	+0.3	196.0	30.6	26.7	0.5	1.48	
15	12	10/6	2425	10600	-1.9	228.0	22.0	23.6	0.5	0.84	
16	6	10/7	2432	9100	+1.8	72.0	33.8	26.7	0.5	0.30	
16	9	10/7	2414	9520	-0.6	407.0	-0.5	19.7	0.55	1.60	
16	10	10/7	2408	9520	-1.5	385.5	-1.3	17.6	1.0	1.10	
16	12	10/7	2437	10310	+1.3	55.0	30.2	23.3	0.5	0.26	
16	13	10/7	2434	10400	+2.1	34.0	28.0	22.6	1.0	0.32	
16	14	10/7	2431	10500	+1.0	91.0	34.0	26.9	0.7	1.34	
16	16	10/7	2427	10620	+2.6	27.0	23.2	18.2	0.5	0.26	
17	1	10/7	2657	10920	-1.8	3.0	-1.5	-1.5	0.85	0.10	
17	2	10/7	2649	11050	+1.8	3.5	13.4	13.4	0.8	0.10	
17	3	10/7	2648	10980	-1.2	11.8	19.2	14.8	1.4	0.20	
17	4	10/7	2645	11050	+2.5	17.0	32.1	30.2	0.6	0.10	
18	2	10/8	2652	10100	+2.0	43.0	33.5	17.3	--	--	(2)
18	4	10/8	2642	10800	+3.4	34.0	33.5	23.5	0.9	0.25	
19	1	10/9	2434	9420	+2.2	111.0	32.4	22.7	1.0	1.0	
19	3	10/9	2428	9500	+2.0	206.5	26.8	--	--	--	(2)

FLIGHT NO.	RUN NO.	DATE 1962	AIRCRAFT GROSS WEIGHT POUNDS	DENSITY ALTITUDE FEET	WIND COMPONENT MPH	THROTTLE CHOP HEIGHT FEET	THROTTLE CHOP V_{cal} MPH	LANDING V_{cal} MPH	LANDING ΔACC. g's	TIME DELAY SECONDS	NOTES
19	4	10/9	2425	9700	+1.5	156.0	30.6	21.4	1.1	0.60	
20	2	10/9	2651	10510	+1.7	100.0	39.9	--	--	--	(2)
20	4	10/9	2641	10560	-1.1	48.0	32.7	--	0.3	--	(2)
20	6	10/9	2661	10590	+0.8	168.0	36.5	30.0	0.6	1.10	
20	8	10/9	2651	10620	-1.1	175.0	35.5	27.7	0.15	0.90	
20	13	10/9	2654	11100	-1.6	278.0	23.3	25.6	0.65	1.40	
20	15	10/9	2642	11150	+0.8	486.0	0.8	21.1	3.1	1.50	(1)
21	4	10/15	2655	9200	-0.7	41.0	27.8	19.4	1.3	0.31	
21	5	10/15	2648	9200	-1.0	94.0	34.8	21.8	1.0	0.30	
21	6	10/15	2644	9310	-0.8	38.0	29.6	22.3	2.1	0.30	
22	2	10/15	2443	10200	+0.9	164.0	32.0	24.3	0.65	0.96	
25	4	10/18	2832	4820	+6.1	73.5	36.3	32.5	0.2	0.20	
25	6	10/18	2849	4880	+3.7	26.5	34.4	31.8	0.6	0.25	
25	8	10/18	2841	4980	+2.8	27.5	33.2	26.8	0.5	0.25	
25	9	10/18	2851	5050	+3.6	159.5	30.4	28.1	0.7	0.57	
26	3	10/19	2838	3580	+2.5	50.5	35.4	28.2	0.7	0.25	
26	4	10/19	2857	3580	+3.9	97.5	34.4	28.6	0.2	0.25	
26	5	10/19	2851	3580	+4.9	105.5	34.0	31.4	1.0	0.27	
26	9	10/19	2851	3660	+3.9	221.5	24.3	25.8	0.2	0.67	
26	10	10/19	2847	3650	+3.0	53.5	31.7	27.0	0.45	0.27	
27	6	10/20	2844	3680	+1.5	10.5	20.5	19.7	0.6	0.14	
27	7	10/20	2836	3680	+1.3	10.0	12.8	12.8	0.4	0.13	
28	4	10/20	2644	3750	-3.7	8.0	-3.5	-3.5	1.4	0.14	
28	6	10/20	2838	3880	-1.1	5.5	-1.1	-1.1	0.75	0.08	
28	8	10/20	2642	4020	+0.8	12.5	13.5	13.5	0.75	0.10	

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28	11	10/20	2653	4100	+1.3	18.5	20.6	16.3	0.7	0.10	
28	14	10/20	2644	4400	+0.2	72.5	30.2	23.2	0.6	0.23	
28	16	10/20	2648	4610	-0.4	99.5	28.1	22.7	1.1	0.17	
28	19	10/20	2636	4700	+4.4	162.5	26.5	28.6	0.3	0.27	
28	23	10/20	2642	4900	+3.2	149.5	27.9	29.5	0.75	0.75	
28	24	10/20	2639	4910	+1.5	40.5	26.0	17.0	0.9	0.24	
28	25	10/20	2635	5010	-0.7	319.5	0.7	19.4	0.65	1.20	
29	2	10/21	2644	6970	+1.4	6.0	1.3	1.3	0.8	0.30	
29	3	10/21	2638	7000	+1.2	10.0	12.1	14.0	0.8	0.35	
29	5	10/21	2626	7080	+0.6	16.0	19.6	19.6	1.0	0.30	
29	8	10/21	2646	7280	-2.3	36.0	27.2	21.4	1.2	0.28	
29	10	10/21	2638	7350	-1.4	56.0	34.0	28.2	0.6	0.23	
29	11	10/21	2657	7400	+1.0	66.0	32.8	26.2	1.3	0.29	
29	13	10/21	2645	7700	+0.7	110.0	34.7	28.4	0.3	0.97	
29	15	10/21	2650	7860	+0.6	162.0	34.0	28.8	0.3	0.76	
29	18	10/21	2636	8180	-3.8	248.5	19.7	28.1	0.75	1.00	
30	9	10/22	2638	7150	+0.8	332.0	4.1	19.0	0.4	1.10	
31	2	10/22	2852	7500	+1.1	3.8	1.0	1.0	0.9	0.0	
31	3	10/22	2848	7500	-2.0	5.0	10.1	10.1	0.8	0.27	
31	4	10/22	2844	7520	-0.5	11.0	19.3	16.5	1.0	0.27	
31	5	10/22	2840	7580	-0.7	17.0	29.5	24.8	1.15	0.33	
33	2	10/26	2419	7010	+2.4	6.8	2.4	2.4	1.1	0.28	
33	4	10/26	2413	7090	+1.4	10.0	12.3	12.6	0.6	0.28	
33	6	10/26	2407	7180	+3.0	19.5	22.5	21.2	0.2	0.36	
33	8	10/26	2418	7180	+3.1	35.0	29.0	19.6	0.2	0.30	
33	9	10/26	2413	7300	+1.8	65.5	28.4	20.4	1.1	0.25	
33	11	10/26	2403	7300	+0.3	112.0	26.7	24.7	0.3	0.22	

FLIGHT NO.	RUN NO.	DATE 1962	AIRCRAFT GROSS WEIGHT POUNDS	DENSITY ALTITUDE FEET	WIND COMPONENT MPH	THROTTLE CHOP HEIGHT FEET	THROTTLE CHOP V_{cal} MPH	LANDING V_{cal} MPH	LANDING ΔACCL g's	TIME DELAY SECONDS	NOTES
33	13	10/26	2420	7550	-2.6	137.0	29.5	20.8	0.5	0.80	
33	16	10/26	2413	7880	-1.6	162.0	29.1	27.5	0.3	0.99	
33	18	10/26	2405	7920	-2.2	196.0	23.4	23.4	1.0	0.96	
33	20	10/26	2397	8100	-2.4	300.0	-2.1	18.4	0.3	1.1	
34	2	10/27	2421	6500	-1.4	29.0	24.3	18.2	1.2	0.0	
34	5	10/27	2412	6550	-1.4	7.0	-1.3	-1.3	0.9	0.0	
34	6	10/27	2409	6580	-1.9	18.0	16.0	12.5	0.7	0.25	
34	13	10/27	2648	7270	-1.5	217.0	27.8	27.8	0.4	1.30	
35	8	10/31	2414	870	-0.3	16.7	-0.3	-0.3	2.1	0.25	
35	10	10/31	2407	900	-0.6	20.0	9.3	8.4	1.0	0.24	
35	14	10/31	2421	1180	-0.4	9.0	-0.4	-0.4	0.4	0.0	(3)
35	15	10/31	2418	1180	+0.8	8.7	+0.8	+0.8	0.9	0.0	(3)
36	2	11/1	2416	0	-2.8	11.7	-2.8	-2.8	0.9	0.0	(3)
36	4	11/1	2411	50	-2.2	18.3	-1.5	-1.3	2.3	0.15	(4)
36	10	11/1	2416	300	-2.6	51.0	13.8	10.6	1.25	0.29	
37	1	11/3	2659	410	-2.0	8.0	-1.3	-1.0	1.7	0.0	
37	4	11/3	2648	580	-0.7	30.0	20.6	24.1	0.6	0.26	
38	4	11/4	2403	-100	+1.5	78.0	19.4	12.8	0.8	0.28	
38	5	11/4	2424	0	-0.3	129.0	12.6	13.5	2.3	0.29	
38	11	11/4	2400	200	-3.5	203.0	10.1	19.4	1.3	0.31	
39	1	11/4	2853	300	-0.4	12.0	17.8	16.0	0.7	0.32	
39	4	11/4	2835	580	-2.9	30.0	24.0	24.0	0.8	0.30	
41	5	11/5	2861	340	+2.5	74.0	27.8	21.4	0.5	0.29	
41	6	11/5	2858	420	+1.5	106.0	26.6	22.9	0.7	0.28	
41	14	11/5	2836	530	+1.7	147.0	28.4	23.6	0.7	0.92	
42	3	11/6	2854	-500	-2.9	10.0	-1.9	-1.9	1.7	0.31	

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42	4	11/6	2849	-500	-3.5	6.3	-3.5	-3.5	1.1	0.0	
42	5	11/6	2844	-500	-3.5	8.6	-3.5	-3.5	0.6	0.29	
42	6	11/6	2839	-500	-3.1	10.0	8.0	8.6	1.2	0.31	
42	7	11/7	2834	320	-3.1	16.0	12.5	14.5	1.9	0.32	
42	8	11/7	2829	280	-4.8	24.0	18.4	19.4	1.7	0.30	
42	11	11/7	2844	420	-4.1	160.0	24.0	22.5	0.7	0.95	
42	13	11/7	2847	500	-4.5	131.0	26.9	22.6	1.8	1.00	
43	5	11/8	2424	-500	-1.3	76.0	21.8	16.8	0.35	0.30	
43	6	11/8	2418	-420	-1.6	147.0	15.5	18.9	1.0	0.30	
43	10	11/8	2427	-110	-2.3	228.0	7.9	17.3	0.3	0.67	
43	12	11/8	2421	-50	-3.5	139.0	10.1	15.7	2.3	1.00	
43	13	11/8	2418	100	-3.2	221.0	5.5	16.7	0.9	0.37	
44	2	11/8	2860	200	-3.0	190.0	20.7	18.0	0.5	0.63	
44	3	11/8	2855	200	-2.4	241.0	15.8	20.2	1.1	1.07	
45	2	11/8	2652	470	-2.0	15.0	9.5	10.6	1.4	0.22	
45	3	11/8	2648	440	-1.4	20.0	16.1	18.6	1.0	0.30	
45	7	11/8	2635	530	-2.6	27.0	17.1	17.1	0.85	0.30	
46	2	11/9	2421	-120	-1.7	42.0	15.5	13.4	1.4	0.32	
46	10	11/9	2839	-30	+0.5	283.0	4.8	20.7	1.0	0.90	
47	1	11/9	2656	20	+0.7	37.0	21.7	15.7	0.7	0.28	
47	2	11/9	2653	230	-0.2	43.0	20.3	15.7	0.5	0.29	
47	4	11/9	2647	260	-1.5	72.0	20.2	18.2	1.2	0.32	
47	6	11/9	2641	230	-1.8	123.0	22.6	25.2	0.55	0.87	
47	8	11/9	2662	370	-1.5	114.0	21.8	21.8	0.8	0.86	
47	10	11/9	2653	400	-1.2	167.0	17.3	21.1	0.4	1.00	
47	12	11/9	2644	450	-0.8	217.0	11.9	20.3	0.45	0.85	

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47	16	11/9	2654	610	-0.3	8.7	-0.3	-0.3	2.0	0.32	
47	18	11/9	2648	610	0.0	11.7	0.0	0.0	2.5	0.33	
48	8	11/12	2408	800	+2.5	191.0	12.5	15.4	0.5	1.50	
48	10	11/12	2425	870	+2.1	124.0	21.2	15.5	0.6	0.63	
49	2	11/12	2649	-140	+1.6	258.0	3.4	18.8	1.0	1.20	
50	1	11/12	2855	100	+1.0	337.0	1.0	17.5	0.5	1.20	
50	3	11/12	2846	180	+0.5	10.0	55.0	30.6	0.2	0.0	(3)
50	4	11/12	2841	180	+0.3	4.0	79.9	20.2	0.5	0.5	
51	4	11/27	2847	630	+2.6	34.0	26.0	20.3	1.6	0.18	
51	9	11/27	2848	710	+3.1	79.0	27.3	24.8	1.0	0.28	
51	13	11/27	2834	700	+3.4	111.0	27.7	22.6	1.4	0.46	
52	3	11/29	2860	-300	-1.7	10.3	-1.7	-1.7	0.7	HOLD	
52	5	11/29	2655	-220	-1.8	10.7	-1.8	-1.8	0.9	HOLD	
52	9	11/29	2646	-170	+0.2	20.6	+0.2	+0.2	1.9	0.31	
52	11	11/29	2855	0	+2.3	19.7	12.8	14.0	1.5	0.31	
52	14	11/29	2855	350	+2.7	14.3	10.1	13.2	2.0	0.32	
52	17	11/29	2844	350	+1.2	25.7	13.8	16.8	0.8	0.33	
52	21	11/29	2857	410	+4.2	50.0	24.9	23.2	0.2	0.24	
53	4	11/30	2831	310	+2.2	283.0	+2.2	21.9	0.5	1.00	
53	5	11/30	2860	320	+2.0	116.0	26.1	26.7	0.5	0.80	
53	6	11/30	2874	320	+2.2	120.0	27.5	29.4	1.2	1.23	

(1) Yielded landing gear cross tubes

(2) No oscillograph data recorded

(3) Collective Pitch Application Technique - Pilot maintained prevailing collective pitch setting at time of throttle cut and reserved remaining available collective pitch for arresting his descent at touchdown.

(4) Collective Pitch Application Technique - Pilot lowered collective pitch immediately after throttle cut to prevent excessive rotor speed decay and then applied "full collective" for arresting his descent at touchdown.

FAA ADS-1
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